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Radio Exploration of the Planetary System

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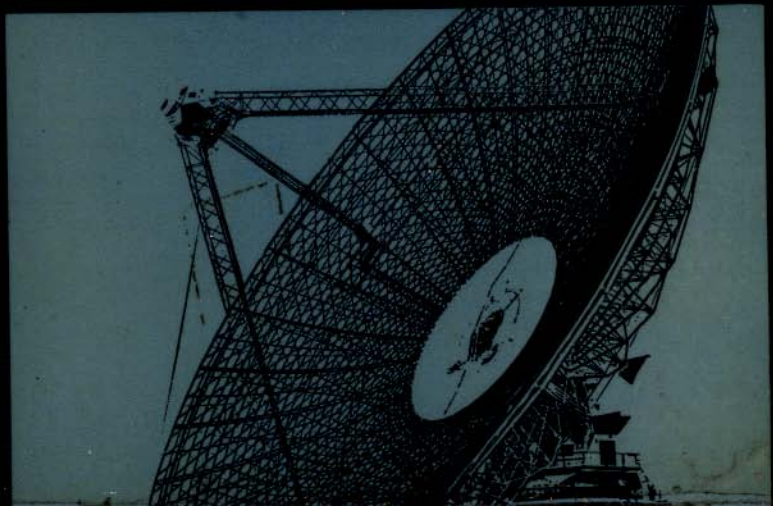
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VAN NOSTRAND MOMENTUM BOOK #2

COMMISSION ON COLLEGE PHYSICS

Radio Exploration of the Planetary System

ALEX G. SMITH AND THOMAS D. CARR



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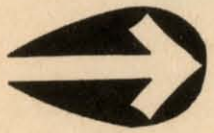
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and T. D. CARR
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RADIO EXPLORATION of the PLANETARY SYSTEM

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Preface

Nine years ago this book could not have been written, for until 1955 there was no science of planetary radio astronomy. Long neglected by professional astronomers, who felt that stars and galaxies were more important, planetary research is enjoying a vigorous renaissance in which radio observations and other techniques borrowed from the physics laboratory play a central role. The driving force behind this revival of interest in the planets is the dawn of the space age and the fact that we can now foresee the day when man himself will set foot on other bodies of the solar system.

So rapid has been the advance of planetary radio astronomy that it is already a problem to select from the large store of available material. We therefore make no claim of completeness; rather we have attempted to acquaint the reader with some of the methods used in the exploration of the solar system by radio and to familiarize him with a few of the more important and more easily understood results of these observations. Because planetary science *is* advancing with almost breath-taking speed, today's "facts" or opinions may be discarded tomorrow. Rather than regarding this as grounds for discouragement or cynicism, the reader should welcome it as proof that science is not a dead body of dogma—it is alive, vital, moving, and there is work to be done.

Like other books of the Momentum series, this volume was written especially for students and others who have an understanding of physics equivalent to that acquired in a beginning course. However, we believe that the general reader with an intelligent interest in science will be able to read most parts of the book without difficulty, and those sections that appear to be too technical can be passed over without serious loss of continuity.

Significant contributions to certain of the studies reported in this book have been made by our students, notably Mr. C. H. Barrow, Dr. N. E. Chatterton, and Dr. N. F. Six, Jr. Equally important has been the assistance of Srs. H. Bollhagen, J. May, and J. Levy at our southern hemisphere observatory, which is operated in cooperation with the University of Chile under the direction of Dr. Federico Rutllant. We are most grateful to the National Science Foundation, the Office of Naval Research, and the Army Research Office (Durham) for financial support. Mr. Hans Schrader, Mr. T. Anderson, and Mr. W. Cain assisted with the illustrations, and we are indebted to Mrs. Sarah Hutton, Helen S. Haines, and Mrs. Margaret McIntyre for the preparation of the manuscript.

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1 *The Beginnings of Radio Astronomy*

The search for celestial radio signals began soon after the discovery of radio waves themselves. Although Maxwell proposed his famous theory of electromagnetic radiation in 1865, it was not until 1888 that Heinrich Hertz produced and measured radio frequency waves in the laboratory. Only six years later Sir Oliver Lodge was telling the Royal Institution of Great Britain, "I hope to try for long-wave radiation from the sun, filtering out the ordinary well-known waves by a blackboard or other sufficiently opaque substance."

From Lodge's later description of the apparatus with which he actually performed this experiment some time prior to 1900, it appears that the "long-wave radiation" he had in mind lay in the centimeter region of the radio spectrum. Sir Oliver attributed the negative results of his experiment to "too many terrestrial sources of disturbance" and added that "clearly the arrangement must be highly sensitive in order to succeed." In view of the latter remark it is worth noting that Lodge's detector was a simple coherer, or tube of metal particles, connected in series with a battery and a galvanometer.[1]

In September of 1900 Charles Nordmann, a French graduate student, independently attempted a similar experiment. He used two different coherers and an antenna 175 meters long, and set up his apparatus on a glacier at an altitude of 3100 meters "to eliminate, as much as possible, the absorbing action of the atmosphere." In his doctoral dissertation Nordmann refers to still earlier experiments apparently performed in 1896 by Wilsing and Scheiner at Potsdam as "the first experimental research on electromagnetic radiation from the sun."[2] With remarkable foresight, Nordmann predicted that strong outbursts of solar radio

waves would be associated with sunspot activity, and so certain was he of his ground that he blamed the negative results of his experiment entirely on atmospheric absorption, never doubting the existence of "les radiations hertziennes."

Thus, within little more than a decade after Hertz's discovery of radio waves, at least three groups of scientists had actively attempted to detect extraterrestrial radio signals. Unfortunately, three more decades were to elapse before the electronic art had advanced to the point where such observations could succeed. It is somewhat ironic that the actual discovery, when it came, was purely accidental, and that the source detected was not the sun, which had been the logical objective of the early experimenters.

JANSKY AND THE COSMIC RADIO NOISE

In 1928 a young physicist named Karl Jansky joined the staff of the Bell Telephone Laboratories. He was assigned to a field station at Holmdel, New Jersey, where he was given the problem of studying static and other forms of interference which caused trouble in commercial radio telephony. By 1930 Jansky had designed and constructed a large directional antenna, which operated at a frequency of 20 megacycles per second (Mc/sec). As we see in Plate I, the antenna was mounted on a kind of merry-go-round so that it could be turned in any direction in order to pin-point sources of interference.

Jansky's records showed the expected static bursts from both local and distant thunderstorms, but in January of 1932 he became aware of a different kind of signal, which he described as "a hiss in the phones that can hardly be distinguished from the hiss caused by set noise."[3] It was at this point that Jansky displayed the qualities of a true scientist and thereby gained immortality. Instead of dismissing the mysterious hiss as "unimportant," he set about tracking it down and spent a year making careful records of the noise.

Not only did the strongest signal seem to come from a definite direction, but that direction moved around the horizon from east to west during the day. At first the movement seemed to coincide with that of the sun, and Jansky naturally suspected that the sun

was the source of the hissing noise. However, as the months went by the noise got more and more out of step with the sun. By this time Jansky, with characteristic thoroughness, had educated himself in the fundamentals of astronomy, and he came to realize that the hiss was coming from a point in the sky that remained fixed with respect to the *stars*. In fact, the noise seemed to be coming from the direction of the center of our Milky Way system—that is, from the center of our galaxy.

Thus Jansky, at the age of 26, became the first successful radio astronomer—the discoverer of the so-called "cosmic radio noise." Later generations of radio astronomers have devoted much time and effort to producing maps of this noise at many different frequencies. These maps, made with equipment far more sensitive than Jansky commanded, show that cosmic noise emanates from all parts of the sky. However, the signal is far stronger in the plane of the Milky Way and it reaches a maximum in the zodiacal constellation Sagittarius, which happens to lie in the direction of the center of the galaxy. Cosmic noise is most intense at the lower frequencies, but it stretches in a broad and continuous band across the whole radio spectrum. Present-day theorists believe that this noise is largely "synchrotron radiation" emitted by high-speed electrons spiraling in weak magnetic fields in the vast reaches of space between the stars.

THE DEDICATED AMATEUR

It is one of the curiosities of the history of science that after a brief splurge of publicity Jansky's discovery excited little interest. Because cosmic radio noise appeared to be too weak to be of practical importance, Jansky was not encouraged to continue his research, and neither astronomers nor radio engineers seemed ready to follow it up. For a decade the only work done in radio astronomy was that of a dedicated amateur, Grote Reber.

Intrigued by Jansky's published papers, Reber constructed a parabolic reflector 31 feet in diameter in his back yard in Wheaton, Illinois.[4] He chose this form of antenna because he had correctly decided that in order to achieve high resolving power—that is, ability to discriminate between closely spaced

sources—it would be necessary to work at high frequencies. The reflector consisted of a sheet metal "skin" attached to a wooden framework. It was mounted in such a way that it could be tipped up and down about a horizontal east-west axis, but for reasons of economy it could not be rotated in azimuth. Thus the antenna could scan any celestial object once a day as that object crossed the meridian, the imaginary line in the sky running from the north point on the horizon through the zenith to the south point on the horizon.

This instrument, which can properly be regarded as the ancestor of the great radio telescopes of today, was placed in operation early in 1938. It is a tribute to Reber's perseverance that he experimented for more than a year with various receivers and detectors placed at the focus of the mirror before a single positive result was obtained. Finally, in April of 1939, detection of radiation from the Milky Way at a frequency of 162 Mc/sec initiated a long series of observations that finally led to the publication in 1944 of a complete map of the cosmic radio noise at that frequency.

The experiments at Wheaton continued until 1947, when both Reber and his 31-foot radio telescope moved to the National Bureau of Standards field station in Virginia. Oddly enough, the founder of high-frequency radio astronomy is now working at the other extreme of the radio spectrum. From selected sites in the southern hemisphere Reber is attempting to make observations of cosmic noise at frequencies of only a few Mc/sec through hypothetical "holes" in the earth's ionosphere.

THE SUN AT LAST

During February of 1942 British antiaircraft radars operating in the frequency range from 55 to 80 Mc/sec suddenly began to suffer severe interference. Only a few days earlier the German fleet had been active in the English Channel, and there was considerable apprehension that the Germans were jamming the radars preparatory to launching an offensive. An operational research team directed by Stanley Hey was sent to investigate the trouble.

Since the radar antennas were highly directional and could easily be pointed at any part of the sky, it was not difficult to track down the source of the interference. Within a few days Hey was able to report that it was the sun, rather than the Germans, which was jamming the sensitive receivers. Noting that a large sunspot was visible at that time, Hey even concluded—correctly, as we now know—that the unusual radio outburst was in some way associated with sunspot activity. After a lapse of forty years, Charles Nordmann's "educated guess" had been confirmed.[5]

Only four months later, in June of 1942, G. C. Southworth of the Bell Telephone Laboratories independently detected solar radio emission. Although Southworth also used radar equipment, his results were not accidental, but were achieved through a deliberate search for solar radio waves. Southworth's observations were made in the microwave region, at frequencies of 3000 and 10,000 Mc/sec. The radiation that he measured was largely simple thermal or "heat" radiation, rather than the more powerful sporadic outbursts that Hey had identified at the lower frequencies.

Because of war-time restrictions, the work of Hey and Southworth was kept secret, and in September of 1943 Grote Reber became the third independent discoverer of solar radio emission. Reber used his 31-foot parabola with a 160 Mc/sec receiver and reported that "On the very first try the quiet sun put the pen hard against the pin at full scale for half an hour near meridian transit." [4]

Nearly half a century had elapsed since the earliest attempts to detect solar radio waves. Then, within less than two years, three different observers independently achieved success. It has often happened that scientific research has had to wait for technological advances. Once these advances have been made, many clever people are capable of utilizing the new technology to make scientific breakthroughs.

It has been estimated that up to the present time over one-third of the total effort in radio astronomy has been devoted to studies of the sun. We now know that the radio spectrum of the sun is one of enormous complexity, with at least five different types of transient outbursts being recognized in addition to the steady

thermal radiation that the sun emits as a hot body. The present book deals with the radio astronomy of the solar system, but the topic of the sun is so extensive that its treatment requires a separate volume.

RADIO STARS

Immediately after World War II, Stanley Hey began using modified 64-Mc/sec antiaircraft radars to map the cosmic radio noise. In 1946, he and his colleagues unexpectedly found a region in the constellation Cygnus that seemed to show marked fluctuations in intensity.[6] In fact, large and erratic changes in signal strength occurred in periods of a minute or less. Hey and his associates concluded that the source (or sources) responsible for this radiation must be physically quite small, since it was difficult to see how an extensive body could change so rapidly.

In 1948 the Australians J. G. Bolton and G. J. Stanley were able to show that the angular size of the Cygnus source was less than 8 minutes of arc.[7] It has also been demonstrated that the fluctuations are actually a kind of "twinkling" effect caused by the earth's ionosphere rather than an intrinsic variation of the source itself. The scintillations are prominent because of the small angular size of the source, just as stars appear to twinkle at night while planets, which subtend much larger angles, usually do not.

Because of its small extent, the new source was referred to as a "radio star," and it was given the designation Cygnus A. During the intervening years, over 2,000 such objects have been mapped by radio astronomers working largely in England and Australia. Only one of these sources exceeds Cygnus A in intensity. Much effort is currently being devoted to identifying these radio sources with optical objects. A few appear to be debris of exploded stars, or supernovae, belonging to our own galaxy. The vast majority, however, are apparently associated with other galaxies of a peculiar nature. Some of these systems have been interpreted as two galaxies in the process of collision, while others are galaxies from which great tidal jets have been drawn or ejected. Since it is clear that most of the "radio stars" are not really stellar in nature, astronomers now prefer to call them "discrete sources."

THE HYDROGEN LINE

The sources that we have discussed thus far all radiate broad, ill-defined bands of frequencies covering much of the radio spectrum. In 1944 H. C. van de Hulst of the Netherlands suggested on theoretical grounds that neutral hydrogen atoms should emit a single sharp spectral line at a frequency of 1420 Mc/sec. Because interstellar space was believed to be permeated with rarefied hydrogen gas, it seemed reasonable to presume that this spectrum line might be detected by radio astronomers. However, it was not until 1951 that the predicted radiation was actually observed by H. I. Ewen and E. M. Purcell of Harvard, for the signal proved to be exceedingly feeble.[8]

A great advance was made possible by this observation of monochromatic radiation. Radio astronomers could now make use of the well-known Doppler effect to measure the *velocities* of hydrogen clouds wherever they could be found. If a cloud is moving away from the earth, the observed frequency is less than 1420 Mc/sec; if the cloud is approaching, the frequency is increased. Since the spiral arms of our galaxy are rich in hydrogen, radio astronomers have already been able to complete a fairly detailed map of the galaxy. This achievement is especially impressive when one realizes that it is a goal which had long eluded optical astronomers because of the obscuring clouds of dust and gas that severely restrict visibility in the plane of the galaxy.

Hydrogen radiation has now been detected in a number of other galaxies, including our neighbors, the Clouds of Magellan. Although searches have been made for other spectral lines, notably those of deuterium and OH, the 1420 Mc/sec line of hydrogen is still the only monochromatic radiation currently available to radio astronomers. If one must be limited to a single element, however, hydrogen is not a bad choice, since it is believed to comprise some 80 percent of all of the matter in the universe!

* * *

In this chapter we have outlined a few highlights of the still brief history of radio astronomy. It is hoped that this treatment

will place the remaining chapters in context and help the reader to see how planetary radio astronomy fits into the over-all fabric of science.

We have deliberately omitted several important events that will be treated in detail later: the measurement of thermal radiation from the moon in 1946 and the radar observations of meteors and the moon in the same year. It was not until 1955 that radio signals from a planet were first detected. Like so many discoveries in radio astronomy, this too came as an accident, but it ushered in an era of interest in the radio exploration of the solar system that is today only in its infancy.

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2 *Tools and Techniques of the Planetary Radio Astronomer*

Many of our readers—especially those with professional or hobby interests in electronics—will be strongly attracted by the technical details of the radio astronomer's workshop. It is to them that this chapter is dedicated. If other readers are more intrigued by the radio astronomer's *results* than they are by his instruments, or if they find the going a bit heavy in Chapter 2, they can move on rather quickly without jeopardizing their enjoyment or comprehension of the chapters that follow.

THE NATURE OF RADIO SIGNALS FROM BEYOND THE EARTH

Radio waves, like light and other forms of electromagnetic radiation, consist of mutually perpendicular electric and magnetic field vibrations which are transverse to the direction of propagation. The two types of vibration travel along together with a velocity of about 3×10^8 meters per second (m/sec) in empty space. For unmodulated waves from a radio transmitter, the electric and magnetic vibrations are essentially sinusoidal and the radiation is almost monochromatic. This is not the case for radio waves from planetary sources. In fact, with the exception of the monochromatic radiation emitted by hydrogen, all of the radiation encountered in radio astronomy is of broad spectral bandwidth. Such signals may be considered to consist of an infinite number of sinusoidal components of different frequency which are continuously distributed over the part of the spectrum occupied by the signal. The over-all spectral bandwidth may be as small as a

few percent of the central frequency, as in the case of the intermittent signals from Jupiter, or it may cover virtually the entire spectrum, as in the case of the thermal radiation from various astronomical bodies. Because instantaneous values of the resultant signal amplitude fluctuate erratically, such a signal is often described as "random noise." This is the type of signal responsible for the hiss heard from a television receiver when it is not tuned to a station. The various kinds of signals encountered in radio astronomy resemble random noise to a greater or lesser extent.

MEASUREMENT PARAMETERS

In order to study astronomical radio signals systematically, we must be able to specify their properties quantitatively. The parameters that must be considered are, first, the strength of the signal in each direction at each frequency and time, and second, the polarization of the waves.

Signal Strength. The signal power utilized by a receiving system is proportional to the effective area of the antenna and to the frequency bandwidth of the receiver. Thus, one measure of the strength of the signal at each frequency is the power per unit wavefront area per unit frequency bandwidth. This quantity is the *flux density S*. In mks units, S has the dimensions of watts per square meter per cycle per second ($w/m^2/cps$). The flux density of a given signal is usually different at different frequencies, and for variable signals S is also a function of time.

The angular width of planetary radio sources, as viewed from the earth, is usually extremely small compared with the angle over which the receiving antenna is sensitive. The size of a source thus cannot be determined directly by sweeping the antenna beam across it. Nevertheless, the source width is an important quantity, as we will see later, and it can be measured by interferometric techniques. The solid angle subtended at the earth by the source is designated Ω, and it is measured in steradians (abbreviated sr).

In Chapter 3 we shall discuss two additional measures of the strength of a source. One of these is known as the *brightness* of

the source, and it is equal to S/Ω. The other is the so-called *brightness temperature* of the radiating body.

Polarization. For the complete specification of a radio signal, its polarization also must be known. Radiation is *linearly polarized* if the vectors representing the electric field at all positions and times are parallel to a fixed plane that is itself parallel to the direction of propagation.

Radiation at a single frequency is *circularly polarized* if at each place the tip of the electric vector executes a circle once each period, and it is *elliptically polarized* if the figure that is traced out is an ellipse. Circular or elliptical polarization is *right-handed* if a right-handed screw that rotates in the same sense as the electric vector also advances in the direction of propagation. The polarization is *left-handed* if the electric vector rotates in the opposite sense. A circularly polarized wave can also be considered to result from two component waves that are linearly polarized in mutually perpendicular planes and are 90° out of phase.

Noise that covers a broad band of frequencies can also be circularly or elliptically polarized. In this case the tips of the electric vectors representing those frequency components contained in any small bandwidth Δf (where $\Delta f \ll f$) trace out circles or ellipses once each period. As a consequence of random noise fluctuation, the circles or ellipses produced by the frequency components within the band Δf change in amplitude and phase over time intervals of the order of $1/\Delta f$, but they maintain the same shape, orientation, and rotational sense.

Radio noise is *unpolarized* or *randomly polarized* if the electric vector at every place fluctuates randomly in direction as well as in amplitude (although it always remains perpendicular to the direction of propagation). A beam of unpolarized radiation can be resolved into two independent component beams which are linearly polarized in mutually perpendicular planes. On the average half the power of the unpolarized beam resides in each of the linearly polarized components.

RADIO TELESCOPES

There is great diversity in the types of apparatus used for studying radio signals of extraterrestrial origin. All, however, are

referred to as "radio telescopes." Although radio telescopes designed for different functions may be strikingly different in appearance, they possess the same basic components: an antenna to capture the radiation, a receiver to convert it into current which can actuate a recorder, and the recorder itself.

In the detection of relatively weak and small sources, very large antennas may be required. There are two reasons for this. First, the effective area must be sufficiently large for the antenna to capture enough energy to be measurable in the presence of the noise unavoidably generated by the receiver itself. Second, because of diffraction the angular resolution of any telescope, either radio or optical, improves with each increase in the ratio of the aperture to the wavelength (by "aperture" one means the width of the antenna or lens).

The telescopic images of stars, which are essentially point sources of light, are in reality diffraction patterns. The angular spread of the central maximum of each of these diffraction patterns is approximately λ/D radians, where λ is the wavelength and D is the diameter of the telescope objective. This statement is true if the telescope is perfectly constructed; otherwise the images will be even larger.

Similarly, when the antenna of a radio telescope is swept across a point radio source, radiation is received over an angle of approximately λ/D radians, where in this case D is the effective width of the antenna. Thus two small sources will appear as a single source if their angular separation is significantly less than λ/D, and they cannot be resolved.

The minimum angle of resolution for the largest optical telescopes is less than 10^{-5} degree. Because of the enormously greater wavelengths employed in radio astronomy, the minimum angles of resolution for radio telescopes are far larger. With the largest paraboloidal antennas operating at relatively short wavelengths (for example, 21 cm), the minimum angle of resolution is greater than $\frac{1}{10}$ degree. However, better resolution can be achieved by interferometric techniques, as we will show later.

The frequencies that have been used in planetary radio astronomy range from about 5 Mc/sec ($\lambda = 60$ m) to 75,000 Mc/sec ($\lambda = 4$ mm). The useful spectrum is limited at the low-fre

quency end by the opacity of the earth's ionosphere, and at the high-frequency end by the opacity of the troposphere. The factor that limits the *sensitivity* of a well-designed radio telescope at the lower frequencies is the cosmic radio noise, which is strongest at the lowest observable frequencies, as is discussed in Chapter 7 and illustrated in Fig. 7-1. However, the strength of planetary radio noise relative to this inevitable background of galactic noise can be increased by increasing the size of the antenna.

The situation at the high-frequency end of the spectrum is quite different, since the cosmic noise decreases with increasing frequency, while the noise generated in the receiver itself tends to increase. The internal noise is due to current fluctuations in the circuit elements, caused by thermal activity of the electrons. With conventional receivers the internal noise becomes a more serious limitation than the galactic noise at frequencies higher than a few tens of Mc/sec. However, since 1956 two radically new types of low-noise receivers have been developed which change the picture considerably. These new receivers are the *maser* and the *parametric amplifier*. They permit a reduction of the internal receiver noise by a factor of a hundred, corresponding to a hundred-fold increase in the over-all sensitivity of radio telescopes at the higher frequencies. With the new receivers, internal noise is negligible in comparison with galactic noise at frequencies up to a few hundred Mc/sec. At such high sensitivities the thermal radiation from the ground that leaks into the side or back of the antenna may be comparable to the galactic noise. In some instances it may be the factor that limits the sensitivity of the radio telescope.

Properties of Antennas. Before discussing the various special types of antennas used in radio telescopes, it will be helpful to define some of the parameters by which the properties of antennas are specified. The most important parameters for the present discussion are the directional pattern, the beamwidth, the effective area, the gain, the directivity, and the bandwidth. These and certain related quantities are equally applicable to an antenna whether it is used for receiving or transmitting. The equivalence of each of these parameters for reception and for transmission is known as the "principle of reciprocity." It is often

easier to analyze or to test an antenna when it transmits than when it receives. Thus the reciprocity principle can be an aid in understanding the mode of operation of certain receiving antennas, as well as in making experimental calibrations of them.

The *directional pattern* of a single-beam antenna is illustrated in Fig. 2-1. This pattern is a polar representation of the relative

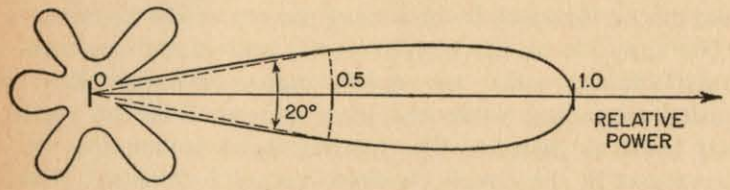


FIG. 2-1 The directional pattern of an antenna.

output power due to the signal from a distant point source of constant intensity, as the antenna is rotated 360° about an axis perpendicular to the direction of the source. Another such plot, obtained by rotating the antenna about a second axis perpendicular to the first and to the direction of the source, is necessary for the complete specification of the directional pattern in three dimensions. Directional patterns usually consist of a main lobe and several secondary lobes, as in Fig. 2-1. Secondary lobes are often unavoidable, but they can frequently be made very small by proper design of the antenna.

The *half-power beamwidth* of the main lobe is the angle between the two directions in which the received power is half of what it is in the direction of maximum power. For example, the half-power beamwidth in the case of the pattern illustrated in Fig. 2-1 is 20°. For a given antenna, the beamwidths are usually different in two mutually perpendicular planes. The beamwidth in radians is generally of the same order of magnitude as λ/L, where λ is the wavelength and L is the maximum linear dimension of the antenna in the plane in which the beamwidth is measured.

The *effective area* of an antenna is a measure of the wavefront area from which the antenna can extract energy. It is defined by the relation $P = SA(\Delta f)$, where S is the flux density of the polarization component to which the antenna is sensitive, A is the effective area of the antenna for this polarization, and P is the power of a signal of bandwidth Δf that is delivered to a matched receiver. The effective area is a function of the direction of the incident radiation, and it is a maximum when the radiation arrives along the main lobe axis. The effective area is usually between 0.5 and 0.9 of the actual area for the larger paraboloidal antennas and broadside arrays.

The directivity and gain of an antenna are measures of the extent to which transmitted radiation is channeled in a given direction, or received radiation is selected from a given direction. The *maximum directivity* is defined as the ratio of the flux density produced at a large distance in the direction of the main lobe axis, when a certain total power is transmitted, to the flux density that would be produced at that distance if the same power were radiated equally in all directions. The definition of gain is almost the same. The *maximum gain* is the ratio of the flux density produced in the direction of the main lobe axis to that which would be produced at the same distance if the power *supplied to the antenna terminals* were radiated equally in all directions. Thus the two quantities differ only when some of the input power is lost in heating the antenna and is not radiated.

Gain or directivity in any direction other than that of the main lobe axis can be similarly defined. The two quantities are thus functions of direction. In Fig. 2-1, if the scale along the polar axis were multiplied by the maximum gain of the antenna, the curve would then be a plot of gain as a function of direction angle. Gain is proportional to effective area. The two quantities are related by the formula $G = 4\pi A/\lambda^2$, where G is the gain in the same direction as that for which A is the effective area. For single-lobe antennas, maximum directivity is approximately inversely proportional to beamwidth.

The gain of an antenna varies with frequency, usually being greatest at the resonance frequency. The dependence of gain upon frequency follows the familiar resonance curve. The *half-power bandwidth* is the difference between the two frequencies at which the gain is half as great as it is at the resonance frequency.

A resonant antenna that is used for transmission appears to be

a resistance, since it continuously dissipates the power fed into it by the transmitter. The *radiation resistance* is the value of this apparent resistance. If the antenna is used for reception at the resonance frequency, it appears to be a radio-frequency generator having an internal resistance equal to the radiation resistance defined above. For maximum transfer of power from the antenna directly to the receiver, the input resistance of the receiver must be equal to the radiation resistance of the antenna. The antenna and the receiver are then said to be "matched." If the distance between the antenna and the receiver is appreciable, a transmission line having the same characteristic impedance as the radiation resistance of the antenna must be used. However, if appropriate matching transformers are employed, maximum power transfer can still be achieved when the antenna resistance, the characteristic impedance of the line, and the input resistance of the receiver are all different.

Types of Antennas. The possible variations in antenna design are almost endless, and many different types have been employed in radio astronomy. The most widely used of the basic types of antennas is the *dipole,* which appears most often as a component of more complex antennas. If the dipole is a half wave or a full wave in length, it is resonant. For such a dipole in free space, the gain is maximum in those directions that are perpendicular to the dipole, and it is zero in those directions that are parallel to the dipole.

Dipoles are used at all frequencies except the very highest. Transmission lines of the open-wire or coaxial types are usually employed to convey the power from the dipole to the receiver. Fig. 2-2 shows a dipole above a plane reflector. If the distance between the dipole and the reflector is a quarter wavelength, the radiation reflected back to the dipole is in phase with the incident radiation. This results in greater gain for radiation arriving from above the reflecting plane and very low gain for radiation arriving from the opposite side.

Other types of reflectors, such as *corner reflectors* and *paraboloidal reflectors,* may also be used. The corner reflector consists of two intersecting planes, like a partially opened book. The dipole in this case is situated in the space between the two planes,

parallel to the line of intersection. The gain of the corner reflector antenna is somewhat greater than that of a dipole with a plane reflector, but making the planes larger than a certain limiting size adds little to the gain. However, if the reflector is a paraboloidal surface, with the dipole at the focus, there is in

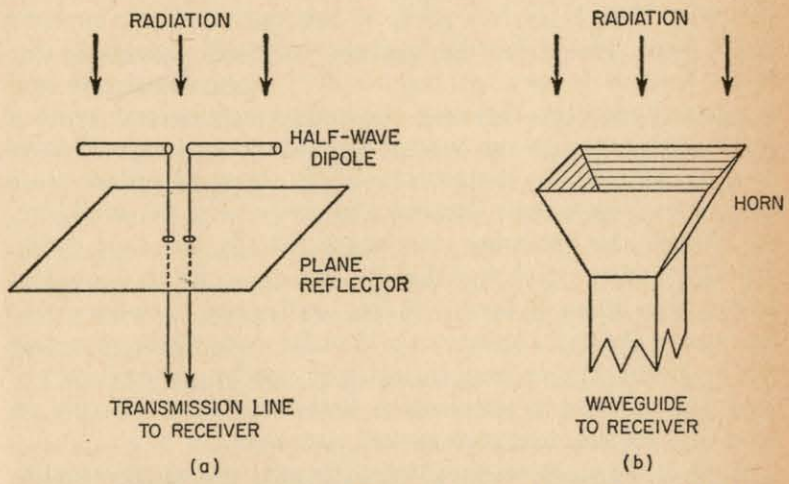


FIG. 2-2 Simple antennas: (a) Dipole above a plane reflector; (b) Horn.

principle no limit to the gain that can be achieved by increasing the area of the paraboloid.

Another simple antenna, which is used only at the higher frequencies, is the *horn.* This antenna is also illustrated in Fig. 2-2. The waveguide shown in the figure is a specially designed pipe that leads captured radiation to a resonant cavity in the receiver. The horn is an enlargement in the open end of the waveguide, being tapered in such a way as to permit maximum transfer of energy from the wavefront into the waveguide. The horn and related waveguide antennas are most useful at frequencies above several hundred Mc/sec. The horn is often used in conjunction with a paraboloidal reflector. In this case, it is placed at the focus in such a position that it collects the radiation reflected from the paraboloidal surface.

The most spectacular of all the antennas of radio astronomy

are the great paraboloids, or "dishes." The largest "steerable" paraboloid now in operation is that at Jodrell Bank, England, which is 250 feet in diameter.[1] A precise and versatile steerable dish 210 feet in diameter has recently been completed in Australia. (See Plate II.) Such large antennas can be effectively operated in any region of the spectrum from about 30 Mc/sec to well over 1000 Mc/sec by using an appropriate dipole or horn at the focus. The higher the frequency at which a given paraboloidal antenna is operated, the narrower is the beamwidth and the greater the gain. However, the highest frequency at which a paraboloidal antenna can be used without serious loss in effective area is determined by the accuracy of the reflecting surface, since departures from a truly paraboloidal shape must be small compared with the operating wavelength (ideally less than $\lambda/15$).

Many smaller paraboloidal radio telescopes are in operation. Dishes from about 50 feet to 90 feet in diameter have been used for most of the radio observations thus far made of the planetary system at the higher frequencies. Still smaller paraboloids are used for millimeter wavelengths because of the difficulty in achieving the required high surface accuracy.

Many of the problems encountered in radio astronomy at millimeter wavelengths are similar to those of optical astronomy. Extreme care is necessary in the manufacture and maintenance of paraboloidal surfaces of the required accuracy. Tolerances in controlling the direction in which the dish is pointed are stringent because of the narrow beamwidth. Observatory sites and observing times must be carefully selected for best "seeing" conditions.

Other types of antennas are superior to the paraboloid at the lower frequencies. For example, beamwidths of a few degrees can be achieved far more economically at meter and decameter wavelengths with a *broadside array*. The broadside array consists of a group of dipoles in rows and columns above a reflecting plane. The dipoles must be connected to the receiver by transmission lines of such lengths that all the signals add in phase at the receiver when the radiation is arriving from the desired direction. To change the direction of the main lobe, either the entire assembly must be rotated (which is physically impracticable at the longer wavelengths), or the transmission line lengths must be so

altered that the signals from the dipoles are in phase only when radiation is received from the new direction.

The *linear array* is a one-dimensional broadside array. For a long, horizontal linear array of length L, the beamwidth in the vertical plane containing L is of the same order of magnitude as λ/L radians. In the vertical plane perpendicular to L the beamwidth is approximately that of a single dipole, including the effect of whatever reflecting surface lies beneath the array. Thus the beam is fan-shaped.

When intermediate gain will suffice, the *yagi* (see Plate III) is probably the most convenient antenna for use at the lower frequencies. In the yagi a half-wave dipole is connected to a transmission line through a suitable matching transformer. Ahead of the dipole are several "directors," and behind it is a "reflector." These additional components, known as "parasitic elements," are simply rods parallel to the dipole and usually differing slightly from it in length.

The operation of the yagi depends on the fact that when radiation passes a parasitic element, the induced current causes the reradiation of some of the power from the incident beam. The secondary radiation, of course, has the same frequency as the original, but different phase. It leaves the parasitic element in all directions except the directions parallel to the element itself. The phase of the secondary radiation reaching any particular point can be changed by a slight variation in the length of the parasitic element. Thus, by adjusting the lengths of the reflector and the directors, it is possible to make the phases of the secondary wave trains such that they all add constructively with the incident radiation at the dipole. The resultant flux density at the dipole is greater than it would have been without the parasitic elements; therefore the gain of the yagi is larger than that of the dipole alone. The greatest advantage of the yagi for planetary observations is its maneuverability.

Arrays of yagis may be used to obtain more gain than a single yagi can provide. The yagis may be arranged in a linear array or in a rectangular array. Approximately the same performance can be obtained from a yagi array as from a broadside array of the same over-all dimensions, although the number of yagis required

to fill the array is much less than the number of dipoles in the corresponding broadside array. If the main lobe of a yagi array is to track a moving source, either the array must be rotated as a rigid structure, or the yagis must track individually, with the lengths of the transmission lines from the yagis to the receiver being continually changed to keep the contributing signals in phase at the receiver input.

The antennas that we have discussed thus far are linearly polarized. However, the polarization of an antenna in the form of a helix is circular, with the rotational sense being the same as that of a point sliding along the helical conductor in the direction of travel of the radiation. Another example of a circularly polarized antenna is the *turnstile*. This antenna consists of a pair of dipoles perpendicular to each other and to the direction of the incident radiation. The signal from one dipole is delayed 90° in phase with respect to that from the other dipole before the two signals are added. The sense of circular polarization to which the antenna is sensitive depends upon which of the two signals is so delayed.

Single-Beam Fixed-Frequency Radio Telescopes. If the planets were the only radio sources in the sky, the detection of their radiation and the measurement of its flux density would be a relatively simple matter. An antenna having a single lobe and adequate gain, a receiver, a recorder, and some means of calibration are all that would be required. The antenna could first be pointed at the planet and then away from it (or the beam could be so oriented that the planet would drift across it) and the difference in recorder deflections noted. Afterward, this deflection could be duplicated by means of a noise signal of known power, obtained from a calibrator connected to the receiver in place of the antenna. From the noise signal power per unit bandwidth and the effective area or gain of the antenna (which can be calculated or measured by standard techniques), the flux density due to the planet could immediately be found.

Actually, this straightforward procedure is applicable to the detection and measurement of the exceedingly feeble thermal radiation from the planets only if a highly directive antenna is available. The beam must be narrow enough so that the cosmic radio noise

that it "sees" is not excessive in comparison with the signal from the planet. With less directive antennas, interferometric techniques may be used to reduce the effect of the galactic noise. The interferometer, which is essentially a multiple-beam antenna, will be discussed later.

On the other hand, the relatively powerful pulses of noise that are often emitted by Jupiter at frequencies below 30 Mc/sec can be detected and measured with the simplest sort of radio telescope. These pulses are so powerful that they often exceed the intensity of the cosmic radio noise, even when received with the simple yagi antenna of Plate III. Plate X shows a large number of Jovian pulses superimposed upon the galactic background, as recorded by a simple radio telescope. The peak flux density of a pulse can be determined, as outlined above, from the difference between the calibrator signal which matches the pulse amplitude and that which matches the undisturbed galactic background, provided the recorder time constant is sufficiently short to display the structure of the pulse accurately.

Receivers and Recorders. Receivers used in radio astronomy are generally of the superheterodyne type, explanations of which can be found in elementary physics or electrical engineering texts. The receiver output is ordinarily connected to a pen recorder, and the pen deflection can be made proportional to the signal power if a square-law detector is used in the receiver in place of the more customary diode detector. Cathode ray spot photography is employed for recording the output of swept-frequency receivers and for studying the detail in Jovian or solar noise pulses. In digital recorders, which are rapidly coming into widespread use, the receiver output is sampled repetitively and is recorded as a sequence of numbers, ready for processing by a computer.

When an observation is made to determine the amount of power received from a constant source of random noise, it is the average power over some brief interval of time that is obtained. Successive measurements will not yield exactly the same value; rather, the values will fluctuate about a mean. If the averaging intervals are made longer, the extent of the fluctuations becomes less, and the averages approach the true mean. The recorder of a

radio telescope indicates the average of the power received over an interval roughly equal to the time constant, τ, of the system. The time constant is largely due to the inertia of the pen, to low-pass filtering between the detector and the recorder, or to a combination of the two. Thus, for the random noise received by a radio telescope, as well as the noise generated internally, the recorder fluctuations can be reduced by increasing the time constant. However, the time constant must be kept small enough so that the recorder can follow any significant changes in the average power of the signal.

The extent of the recorder fluctuations depends also upon the receiver bandwidth, Δf. The bandwidth of the receiver as a whole is practically that of the i.f. amplifier alone, since the bandwidth of the rf amplifier is much broader. Ordinarily, the time required to change the amplitude of oscillation of any resonant system is of the same order of magnitude as the reciprocal of its bandwidth; thus the sharper the resonance, the slower the build-up or decay of oscillations. The power in the i.f. oscillations fluctuates, since the oscillations are derived from random noise. Little change in power can occur in a time interval that is short compared with $1/\Delta f$, but about every $1/\Delta f$ second the power will assume a new value. Thus the i.f. power may be specified, as a function of time, by Δf independent values per second. It is a well-known principle of statistics that for a quantity that is varying randomly about an average, the ratio of a typical fluctuation of the mean of n independent values to the true average is of the order of $1/\sqrt{n}$. During a time equal to the recorder time constant, τ, there are $\tau\Delta f$ independent values; therefore

$$\frac{\Delta P}{P} \approx \sqrt{\frac{1}{\tau \Delta f}}$$

where P is the actual mean power and ΔP is typical of the recorder fluctuations from the mean. Thus the fluctuations can be reduced by increasing the i.f. bandwidth as well as the time constant of the recording system. The maximum usable bandwidth may be determined by equipment limitations, by interference at adjacent frequencies, or by the spectrum of the source itself. The detectability of weak sources and the precision of all

radio-astronomical measurements are limited by such fluctuations in the signal and the background noise.

INTERFEROMETERS

As we have stated, the angular resolution of any radio telescope, in radians, is of the same order of magnitude as the wavelength divided by the maximum linear dimension of the antenna. Detail that is much smaller than this cannot be resolved by the telescope because the antenna beamwidth is too broad. Thus there is no paraboloidal antenna or broadside array in existence that is large enough to resolve the structural detail of a planetary source, or even to obtain a rough idea of the source diameter. However, extremely narrow beams and correspondingly high resolution can be obtained by means of *radio interferometers.*

The Simple Interferometer. The simplest interferometer consists of two antennas of any type which are separated by a distance L that is large compared with the operating wavelength λ; transmission lines bring the signals from the antennas to a junction point, where they are added and fed into a receiver. The operation of the interferometer can be understood with the aid of Fig. 2-3. The two antennas are labelled A_1 and A_2, with A_2 being due west of A_1. The indicated rays, which are assumed to come from a distant point source, make an angle θ with respect to the meridianal plane (that is, the plane that is normal to L). Each wavefront must travel a distance $L \sin \theta$ farther to reach A_1 than to reach A_2. If the lengths of the transmission lines from A_1 and A_2 to the junction are equal, the signal from A_1 will lag that from A_2 by $(L \sin \theta)(360/\lambda)$ degrees of phase when they are added. If the source is a planet or a radio star, θ will increase with time as the source moves across the sky. Whenever the phase difference $(L \sin \theta)(360/\lambda)$ is an integral number times 360° (or the path difference $L \sin \theta$ is an integral number of wavelengths), the two signals will add constructively at the receiver input, and the signal power fed into the receiver will be a maximum. On the other hand, when the phase difference is an odd integer times 180°, the two signals will cancel. Thus, as θ increases, an interference pattern will be recorded as the

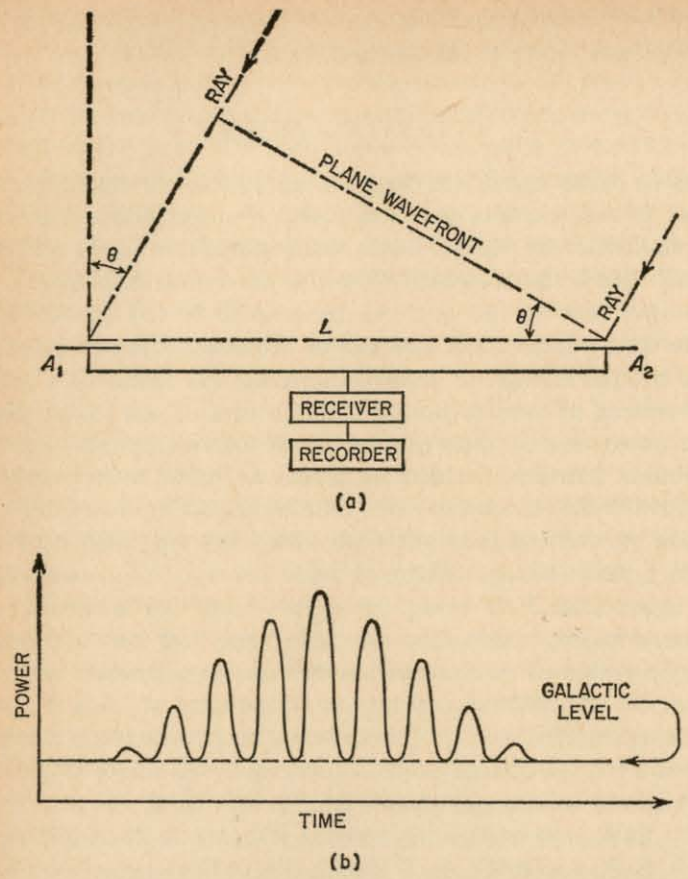


FIG. 2-3 The total power interferometer: (a) Geometry; (b) Record due to the passing of a point source.

received signal passes through successive maxima and minima (the minima will not be zero because of the distributed cosmic noise background).

The condition for the occurrence of maxima is $n\lambda = L \sin \theta$, where n is any integer. Now, each of the antennas A_1 and A_2 has a directional pattern of its own, which is, of course, much broader than the interferometer lobes. If the individual beams of A_1 and A_2 are fixed in the direction of the source when $\theta = 0$, then the

maxima of the lobes (that is, their envelope) will lie along a curve of the same shape as the directional pattern of either of the two antennas. The central lobe (at $\theta = 0$) will be largest, and the others will decrease progressively in the order of their distance from the central lobe. This effect is illustrated by the curve in Fig. 2-3, which represents a plot of receiver output as a function of time as the radio source moves across the sky. This simple type of interferometer is called a "total-power interferometer" because the maximum amplitude of the fringe pattern is proportional to the power incident on the antennas. Thus one of the parameters that can be determined with the interferometer is the flux density S.

In effect, an interferometer converts a relatively broad antenna beam into a large number of narrow, fan-shaped beams capable of greatly increased resolution. This conversion permits the measurement of the angular positions of isolated sources with correspondingly increased accuracy. The angular sizes of sources as small as planets may also be measured.

Two coordinate angles are required to specify any position in the sky relative to the so-called fixed stars. *Right ascension* and *declination* are most often employed. The definitions of these quantities can be found in any elementary astronomy text. On the celestial sphere, declination is more or less analogous to terrestrial latitude, and right ascension to longitude. The right ascension of a radio source can be determined from the time of occurrence of the central maximum of the interferometer pattern and the longitude of the observatory. The declination can be determined from the time interval between two successive maxima, together with the length of the baseline and the wavelength λ.[3] The greater the baseline, the greater the accuracy with which both directional coordinates can be measured.

Actual radio sources are, of course, not points. If the angular width of the source is small as compared with the width of one interferometer lobe, the received pattern is substantially like that of a point source (Fig. 2-3). On the other hand, if the source is broad as compared with one interferometer lobe, the fringes in the interference pattern will scarcely appear at all, as shown in Fig. 2-4a. Instead, there will be a single broad maximum

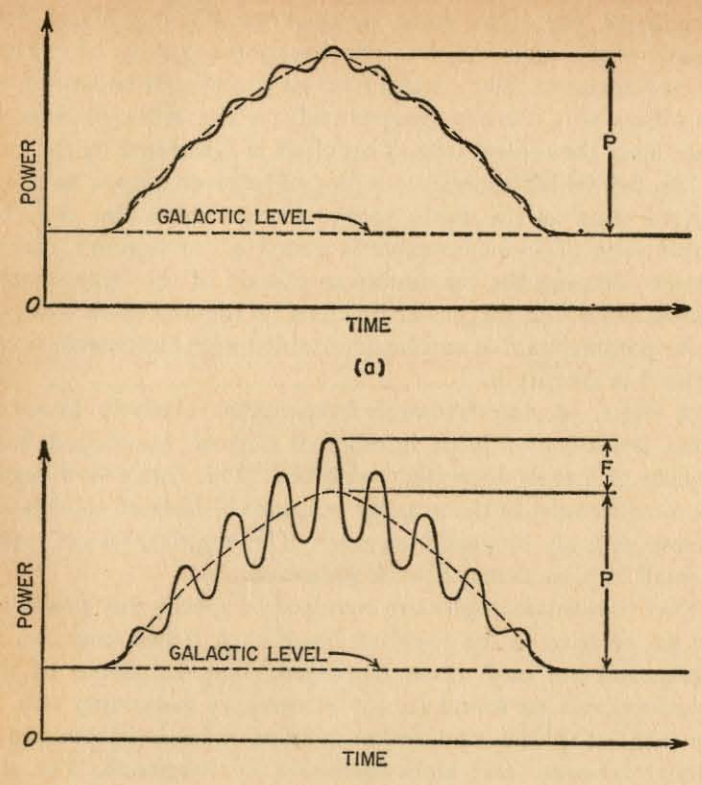


FIG. 2-4 Interferometer records due to sources of appreciable angular diameter: (a) Source width much larger than lobe thickness; (b) Source width comparable to lobe thickness.

corresponding to the directional patterns of the individual antennas (provided the source is narrower than these patterns). The disappearance of the fringes can be explained by assuming the actual source to be a collection of point sources which are distributed over an angle that includes several interferometer lobes. At any given time, some of the point sources will lie in the directions of lobe maxima, but just about as many will be in the directions of lobe minima. Thus in the case of a broad source the fringes are smoothed out.

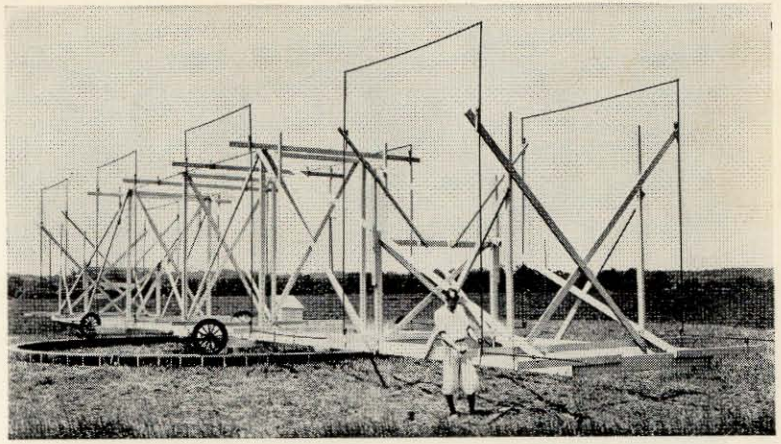


Plate I. Karl Jansky and the rotating antenna with which he discovered cosmic radio noise. (Courtesy Bell Telephone Laboratories.)

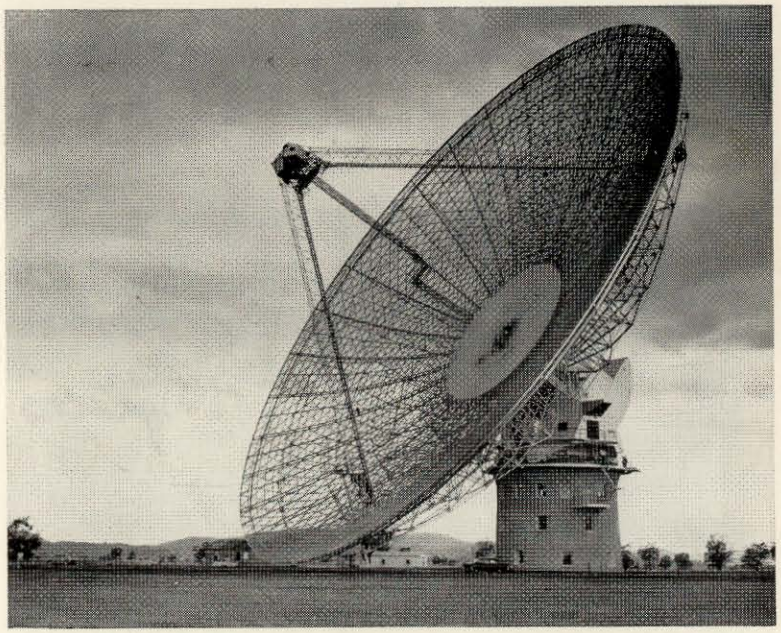


Plate II. Recently-completed 210-foot-diameter parabolic radio telescope of the Commonwealth Scientific and Industrial Research Organization in Australia. (Photograph courtesy of C.S.I.R.O. Radiophysics Laboratory.)

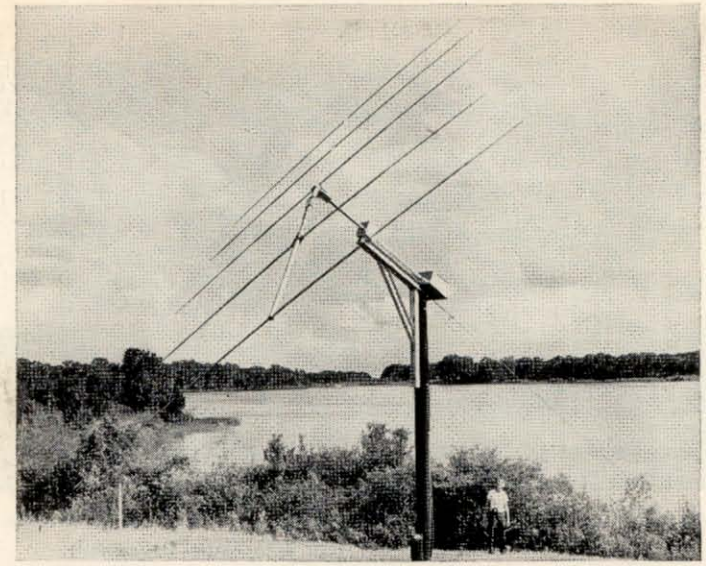


Plate III. An 19 Mc/sec yagi antenna at the University of Florida Radio Observatory. The nearest element is the reflector, the next element is the active dipole, and the three farthest elements are the directors. The antenna is equatorially mounted and motor-driven for automatic tracking of the planets.

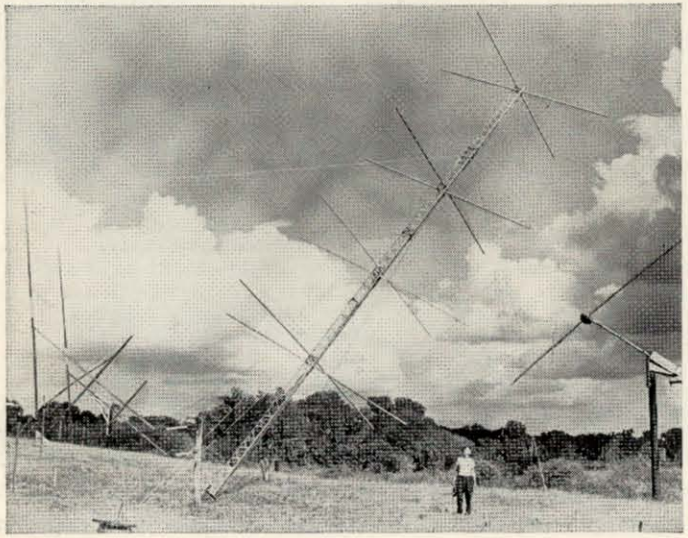


Plate IV. A crossed-yagi polarimeter antenna at the University of Florida Radio Observatory.

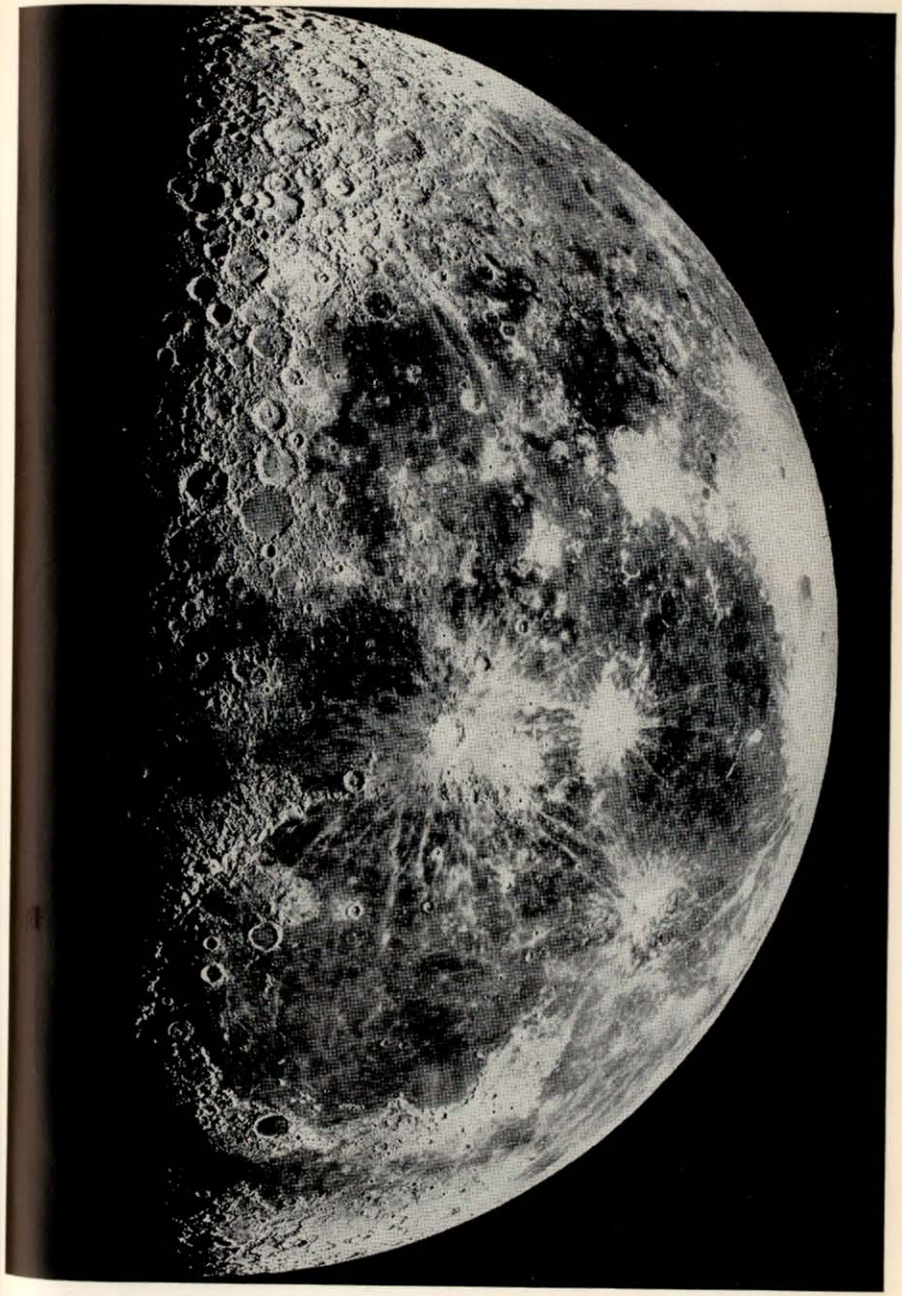


Plate V. A composite photograph of the last-quarter moon taken with the 100-inch telescope at Mount Wilson, showing "seas," craters, and a mountain range (lower left). (Reproduced through the courtesy of the

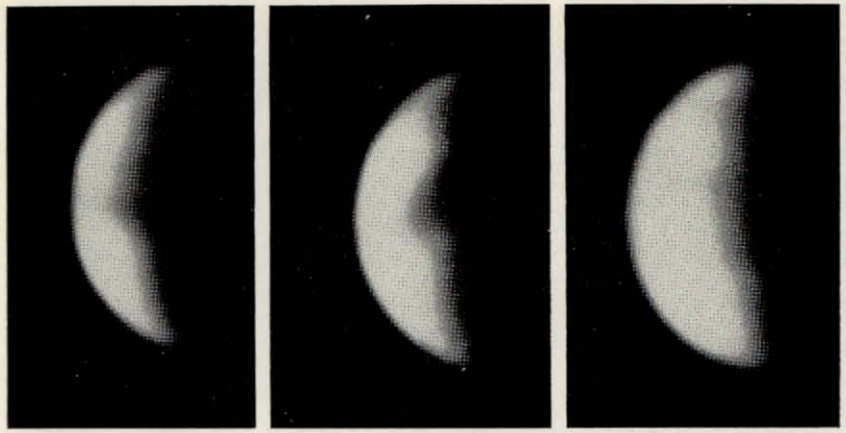


Plate VI. Three photographs of Venus taken with the 100-inch telescope at Mount Wilson. (Reproduced through the courtesy of the Mount Wilson and Palomar Observatories.)

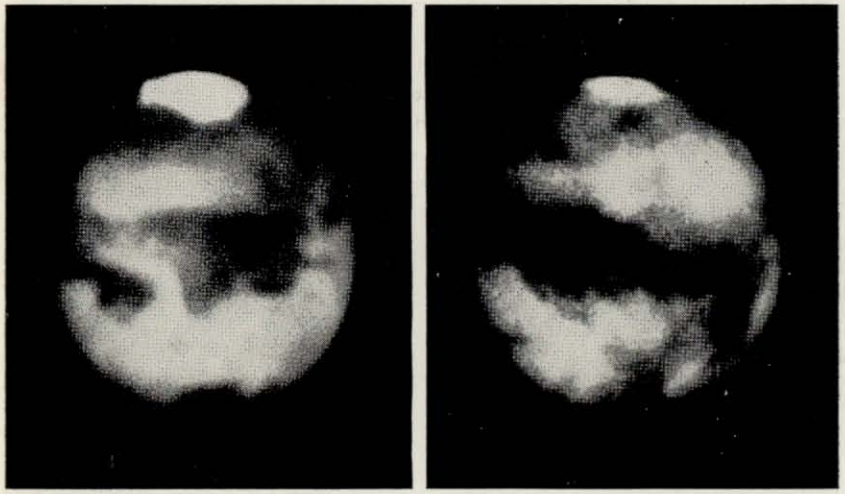


Plate VII. Two views of Mars in 1956 taken with the 60-inch telescope at Mount Wilson, showing opposite hemispheres of the planet. The white area at the top of the disc is the south polar cap. (Astronomical photographs are generally inverted to correspond to the orientation of the object in an inverting telescope.) (Reproduced through the courtesy of the Mount Wilson and Palomar Observatories.)



Plate VIII. A photograph of Jupiter taken with the 200-inch telescope. The large, dark oval near the left margin of the disc is the Great Red Spot. Jupiter's largest satellite, Ganymede, appears above the upper right edge of the planet, and the shadow of the satellite can be seen on the rim of the disc above the Red Spot. Almost in contact with the Red Spot is the long-lived white spot *FA*. (Reproduced through the courtesy of the Mount Wilson and Palomar Observatories.)

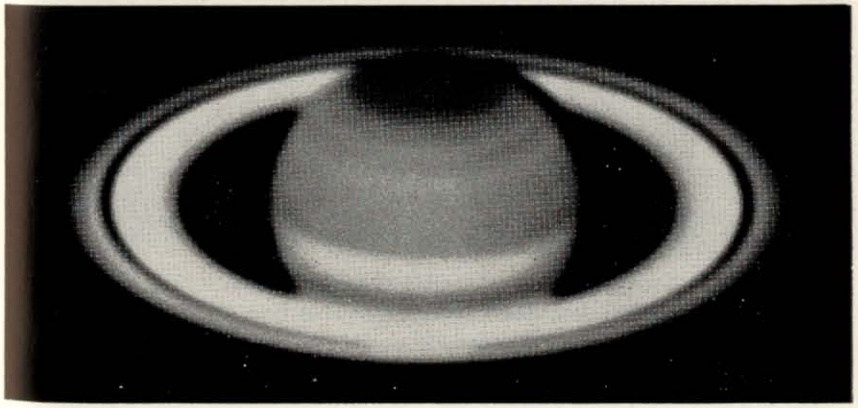


Plate IX. Saturn and its ring system photographed with the 100-inch telescope. (Reproduced through the courtesy of the Mount Wilson and Palomar Observatories.)

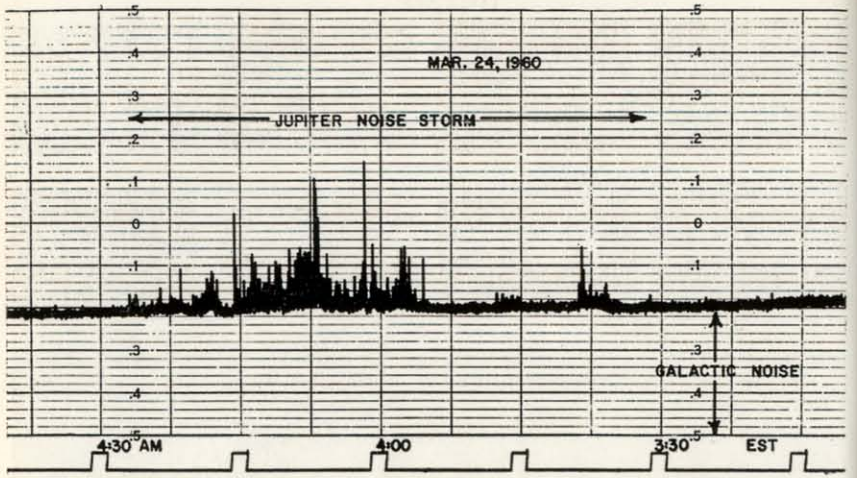


Plate X. Low-speed recording of a Jovian noise storm at 18 Mc/sec. The storm began shortly after 3:30 AM, EST, and lasted about an hour. The Jovian noise bursts are superimposed on a steady background signal from the galaxy—the so-called "cosmic radio noise."

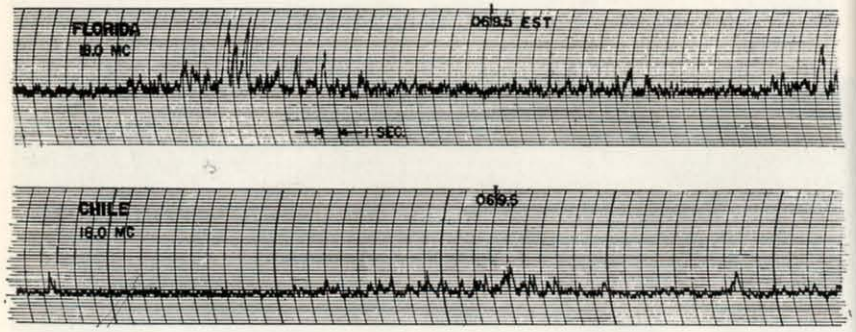


Plate XI. High-speed records of bursts of Jovian radio noise, showing the effect of scintillation. The upper record was made in Florida, and the lower one simultaneously in Chile.

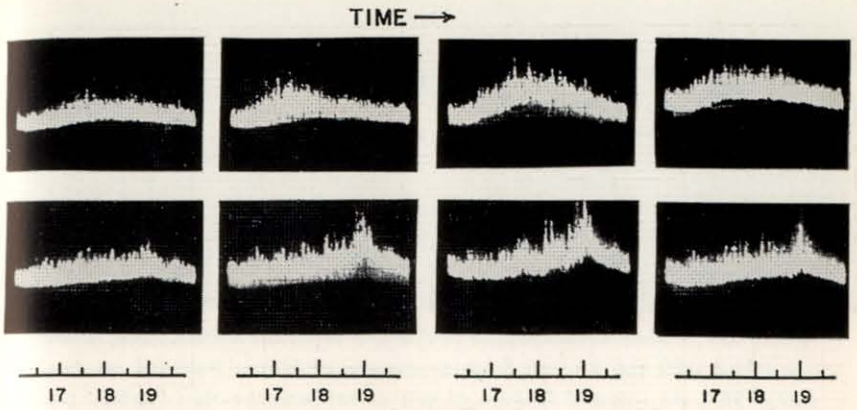


Plate XII. Spectra of Jovian noise bursts, showing the development of two typical pulses. Time increases from left to right in each sequence at the rate of approximately one-half second per frame. A frequency scale is shown at the bottom of the figure.

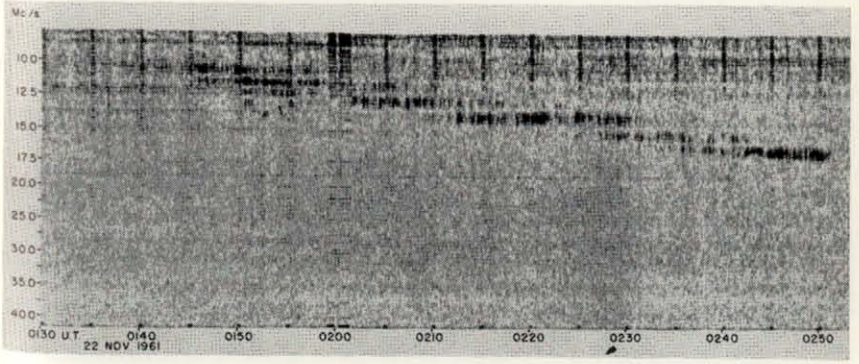


Plate XIII. Frequency drift of a Jovian noise storm. The outburst started near 10 Mc/sec at 1:45 U.T. (Universal Time) and lasted until 2:50 U.T. During this period of 65 minutes the frequency of the storm steadily increased until it reached 17 Mc/sec as the outburst ended. (Photograph courtesy of J. W. Warwick.)

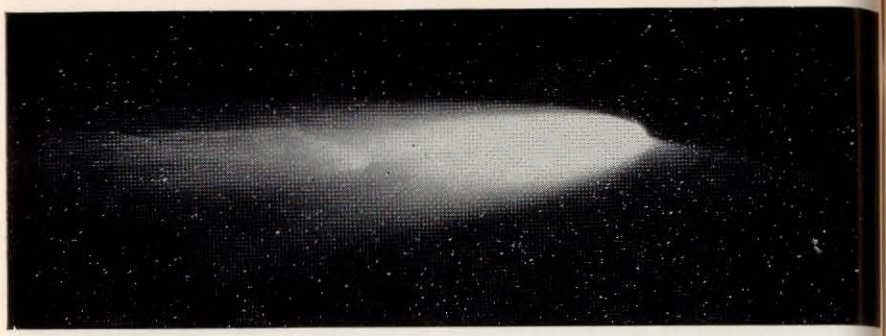


Plate XIV. Comet Arend-Roland (1956h), a reported radio source, photographed with the 48-inch Schmidt camera at Mount Palomar on April 27, 1957. An unusual feature of this comet was the thin "spike" projecting from the head. (Reproduced through the courtesy of the Mount Wilson and Palomar Observatories.)



Plate XV. The Mariner spacecraft. The 20-inch antenna of the microwave radiometer is indicated by the letter M. (Artist's rendering cour-

If the source is nearly the same width as the thickness of one interferometer lobe, the fringes will be present, but they will be smaller than if the source were concentrated in a point. This situation is illustrated in Fig. 2-4b. The dotted line through the fringes represents the total power component; P is proportional to the flux density. The fringe amplitude, F, depends on the source size in comparison with the lobe width. It is possible to determine the angular width and shape of the source in the east-west direction by making a series of recordings with an interferometer having successively longer baseline lengths, and correspondingly thinner and more numerous lobes. In such an experiment the ratio F/P will decrease as the baseline is made longer. From a plot of F/P as a function of baseline length, the east-west distribution of source brightness can be determined for symmetrical sources by utilizing a mathematical tool known as the Fourier transform.[1] The effective source size and its shape are then apparent from this brightness distribution. Baselines up to many miles in length may be necessary in the measurement of a small source. In such a case, radio relay links may be used instead of transmission lines to convey the signals from the two receiving antennas to the junction point.

The Phase-Switched Interferometer. The presence of the cosmic radio noise in the output of a simple interferometer tends to reduce the accuracy with which fringe positions and amplitudes can be determined. If the source is very weak, the interference pattern will appear as a very small oscillation in the recorder trace, superimposed upon a relatively steady deflection caused by cosmic noise. (The latter produces no interference fringes of its own because the galactic source is much wider than the thickness of a single interferometer lobe.)

The *phase-switched interferometer* is a more complicated device in which the cosmic radio noise is eliminated from the recording, so that the only deflections that appear are the interference patterns of sources of small angular diameter. The operation of the phase-switched interferometer depends upon the fact that if the signal from one of the arms of a simple interferometer is shifted in phase by 180° (by the insertion of an extra half wavelength of line, for example), the entire lobe pattern will be

shifted so that minima occur in the original directions of maxima, and vice versa. By means of electronic switching techniques, this 180° phase shift is periodically introduced and removed many times a second, and the signal that is recorded is the difference between the receiver output signals for successive positions of the phase switch.

If, at a given time, a point source happens to lie in a lobe-maximum direction for zero phase shift, and thus in a lobe-minimum direction for 180° phase shift, the difference signal is a maximum. When the source moves into the minimum of a zero-phase-shift lobe—that is, into the maximum of a phase-shifted lobe—the difference signal again reaches a maximum, but in the negative sense. At some point between these two directions the difference signal becomes zero.

Thus, when the difference signal is recorded, fringes are produced similar to those of the simple interferometer. However, the cosmic radio noise no longer contributes to the deflection. Since radiation from the galaxy enters the antenna through all the lobes simultaneously, the shift in lobe directions causes little change in the total galactic noise. The interference pattern from a phase switching interferometer is shown in Fig. 2-5; the fringes

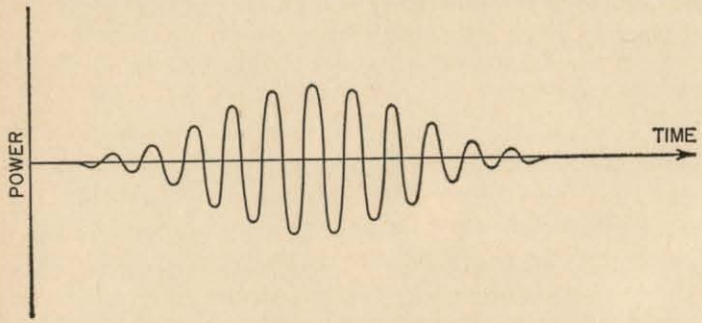


FIG. 2-5. Phase-switching interferometer record.

are now symmetrical about a zero line. The phase-switched interferometer can be used to determine the direction of a source and the flux density of the radiation. However, it cannot be used for the measurement of source size, since the total power com ponent of Fig. 2-4 does not appear in Fig. 2-5.

RADIO SPECTROGRAPHS

The basic components of the *radio spectrograph* are a wide-band antenna, a swept-frequency receiver, and a recorder capable of displaying signal power as a function of both frequency and time. By mechanical or electronic means, the frequency of the receiver is swept repetitively across the spectral region of interest. The recorder may consist of a motion-picture camera which photographs the spot of a cathode ray tube. The spot is swept horizontally in synchronism with the receiver tuning, and it is deflected vertically by the receiver output. Thus the recording consists of a rapid sequence of plots of power as a function of frequency. (See Plate XII.) In another method of photographic recording, the spot is intensity-modulated by the receiver output, instead of being deflected vertically. The film is driven continuously at such a speed that the images of successive sweeps are adjacent to each other. The result is a map of spectral activity in the frequency-time domain. Frequency is plotted in one direction and time in the other; the received power at the point corresponding to each value of frequency and time is depicted by the density of the photographic exposure at that point. Such a time-varying radio spectrogram is shown in Plate XIII.

POLARIMETERS

Radiation may be polarized in many different ways. It may be linearly polarized in any plane parallel to the propagation direction; it may be circularly or elliptically polarized in either the left- or right-handed sense, with a polarization ellipse of any orientation and shape; it may be unpolarized; or it may consist of an unpolarized component and a component having any of the polarizations mentioned above.

The *axial ratio* of the polarization ellipse is the ratio of the length of the major axis to that of the minor axis. Linear and circular polarizations are special cases of elliptical polarization in which the axial ratios are ∞ and 1, respectively. For the specification of the state of polarization of radiation that in

general may be only partly polarized, three numbers are necessary: the axial ratio, the polarization angle, and the polarization fraction. The polarization angle is the angle of inclination of the major axis of the polarization ellipse with respect to a reference plane parallel to the direction of propagation. The polarization fraction is the ratio of the flux density of the polarized component to that of the polarized and unpolarized components combined. The rotational sense of an elliptically polarized wave is designated by the sign of the axial ratio, which is customarily negative for the right-hand sense and positive for the left.

The polarization of radiation from continuously emitting sources can be determined with a total-power interferometer using linearly polarized antennas, such as dipoles. The polarization parameters can be deduced from the amplitudes and relative positions of the interferometer fringes when the dipoles are given various orientations in the horizontal plane.

To determine the state of polarization of radiation from a sporadic source (for example, Jupiter at the lower frequencies), we must use a polarimeter that can make measurements in a time less than the minimum interval during which the signal may vary significantly. One such method employs a pair of crossed yagis (see Plate IV) and utilizes the turnstile principle already mentioned. Electronic switching techniques permit the measurement of right and left circular components and two nonorthogonal linear components, from which the three polarization parameters can be uniquely determined.[4]

EFFECTS OF THE TERRESTRIAL ATMOSPHERE

Incoming radiation that falls perpendicularly upon the ionosphere is reflected back into space if its frequency lies below a certain value. This "critical frequency," as it is called, generally lies between 3 and 8 Mc/sec, varying with ionospheric conditions. Still higher frequencies are reflected if the incidence is oblique. Absorption by oxygen and water vapor in the troposphere, or lower atmosphere, becomes serious above 15,000 Mc/sec. Refraction and scintillation occur even in the spectral region for which the atmosphere is transparent.

Rays penetrating the atmosphere from the zenith are not refracted, but those from all other directions are bent in such a way in both the ionosphere and the troposphere as to increase the apparent elevation of the source. This refraction becomes greater as the angle from the zenith increases. Refraction of radio waves in the troposphere is approximately the same as for light, usually much less than 1°. In the ionosphere the refraction increases as the frequency decreases, and it may be many degrees at low frequencies and large zenith angles.

In Chapter 1 we saw that radiation from celestial sources may fluctuate violently as a result of its passage through the earth's atmosphere. This "scintillation" arises as the radiation passes through the dense *F* region of the ionosphere. Apparently, clouds of ionization that drift about in the *F* region at high speeds act somewhat like moving lenses or diffraction gratings, casting irregular patterns on the ground. In certain areas the intensity will be high, while in others it may be practically zero. These areas move with the same velocity as the ionospheric clouds. As in optics, the smaller the angular size of the source, the more pronounced are the focusing and wave interference phenomena.

The atmosphere is also responsible for much of the interference, both natural and man-made, that is encountered at the lower frequencies. Lightning, which is the source of radio static, is an atmospheric phenomenon, of course. Propagation of both static and the signals from interfering radio stations around the curved surface of the earth depends upon reflection from the ionosphere. Such interference will generally be least when the ionospheric density is lowest, because more of the radiation from the source will escape through the ionosphere, and less will be reflected back to the earth.

For the observation of planetary radio signals at the lower frequencies, we must take advantage of periods when the ionosphere is most transparent, not only to reduce the attenuation of the desired signal, but also to reduce the competition from interfering signals. Because ultraviolet radiation from the sun is responsible for most of the ionization, the density of the ionosphere diminishes after sunset, very rapidly in the lower *E* region, and more slowly in the upper *F* region. Just before the

following sunrise the ionosphere attains its minimum density—that is, its maximum transparency. The ionospheric density also decreases with decreasing sunspot activity, following the familiar 11-year cycle. During winter in years of moderate sunspot activity, stations in the southern United States can make satisfactory observations of sources near the zenith at any hour if the observing frequency is at least as high as 30 Mc/sec. Shortly after sunset the lowest usable frequency drops to about 20 Mc/sec, and between midnight and dawn frequencies as low as 10 Mc/sec can be employed.

Tropospheric absorption limits radio observations above 15,000 Mc/sec. The absorption, which is associated with the rotational energy of the oxygen and water-vapor molecules, occurs strongly in certain frequency bands. Astronomical observations are possible in certain spectral windows between the absorption bands. Such windows are centered at wavelengths of approximately 9 mm, 3.5 mm, 2 mm, and 1.3 mm. Absorption within these windows is still a serious problem, but it may be reduced considerably by locating the observatory at high altitudes and by observing during times of low humidity.

OBSERVATIONS FROM ABOVE THE ATMOSPHERE

Low-frequency ionospheric effects and tropospheric absorption at the high frequencies can be eliminated if observations are made from above the atmosphere. Initial tests have already been conducted with simple radio telescopes in satellites and space probes. Later, larger and more elaborate radio telescopes will be placed in orbit. The antennas for the lower frequencies will probably consist of dipoles of great length, perhaps many hundreds of feet. For the millimeter wavelengths and beyond, small but precise paraboloidal antennas will be employed. As transportation facilities to the moon (and back!) improve, permanent manned radio-astronomical observatories will be established on its surface, probably on the side opposite the earth in order to provide shielding against earth-noises. The vast spectral regions from 10 Mc/sec down to extremely low frequencies, and from

15,000 Mc/sec on into the infrared will then be made accessible for the study of the planetary system and the rest of the universe.

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3. Pawsey, J. L., and Bracewell, R. N., *Radio Astronomy* (Oxford University Press, Oxford, 1955).
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3 *Thermal Radiation from the Moon and Planets*

A broad spectrum of so-called "thermal radiation" is emitted by any object with a temperature above absolute zero. If the object is hot enough it glows with visible radiation and we speak of it as being "incandescent," as in the case of the sun or the filament of an electric lamp. If the body is cooler, most of its emission lies in the infrared part of the spectrum, and the energy is often referred to as "heat radiation." The quantitative explanation of these familiar and seemingly simple facts defied theoreticians until Planck was literally forced into inventing the radical new quantum theory, in order to solve the problem. Thus, one of the most exciting concepts of modern physics sprang from the study of thermal radiation.

THEORY OF THERMAL RADIATION

The Blackbody Curve. Certain fields of physics can be described almost completely in terms of a single curve. The study

of thermal radiation is such a field, and the curve is the so-called "blackbody" curve shown in Fig. 3-1.

What does this graph mean? First, a blackbody is an object which absorbs all radiation that falls on it. In the visible spectrum a surface covered with soot approaches this ideal because it reflects only about 1 percent of the incident light. Since a good absorber is also a good emitter, a blackbody is the most efficient kind of thermal radiator. Fig. 3-1 shows, then, how the power emitted by an ideal radiator at a fixed temperature varies with wavelength. It was the derivation of this curve that led Planck to the quantum theory in the first year of the present century. The ordinate P_λ in Fig. 3-1 is not the power emitted at a single wavelength λ (which would be zero!), but rather the power radiated in a *band* of wavelengths of unit width. That is, if we measure λ in microns, the band is one micron wide. The shaded area in Fig. 3-1 represents such a band.

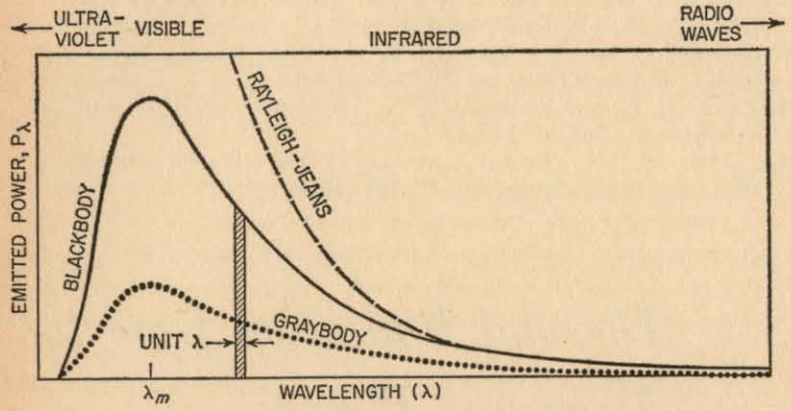


FIG. 3-1 Thermal radiation curves for a blackbody and a graybody at an assumed temperature *T*. If *T* were to increase, the heights of the curves would increase and the peaks would shift to the left.

The Rayleigh-Jeans Formula. Although Planck's equation for the blackbody radiation curve is cumbersome, a simple approximation can be used for the radio wavelengths, which occupy only the right-hand tail of the curve. One of the unsuccessful attempts to solve the blackbody problem was made by Rayleigh and Jeans, whose result is plotted as the dashed curve in Fig. 3-1. The Rayleigh-Jeans formula fits the blackbody data at large values of λ, but near the peak of the curve it breaks down and goes off toward infinity as λ approaches zero. Since the Rayleigh-Jeans equation is simple and performs well in the region in which they are interested, radio astronomers generally use this approximation. In the usual units of radio astronomy, the Rayleigh-Jeans equation can be written as

$$P_\lambda = \frac{2\pi kT}{\lambda^2} \text{ w/m}^2\text{/cps} \qquad (3\text{-}1)$$

where k is the "Boltzmann constant," 1.38×10^{-23} joules per degree. If we combine the numerical factors, Eq. 3-1 becomes

$$P_\lambda = 8.66 \times 10^{-23} \frac{T}{\lambda^2} \text{ w/m}^2\text{/cps.}$$

Let us be certain that we understand the meaning of this important equation: P_λ is the power in watts radiated at the wavelength λ by each square meter of a blackbody whose temperature is T degrees Kelvin. We measure P_λ over a frequency band one cycle per second wide, centered on the wavelength λ, where λ is expressed in meters.

Eq. 3-1 tells us how much power P_λ a body radiates. Actually, the radio astronomer is more directly concerned with the flux density S that is *received* at a great distance from the source. In Fig. 3-2, B represents a planet or other radiating body, while O is an observer at a distance D from this source. By the time it gets to O, the flux that was emitted from the surface area $4\pi r^2$

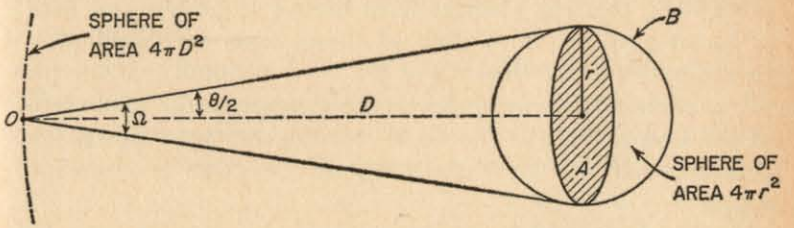


FIG. 3-2 The measurement of radiated power.

of the source is spread over a much larger sphere of area $4\pi D^2$, and consequently the flux *density* is reduced by the factor $(r/D)^2$. (This is, of course, simply the inverse square law.) Thus the observer at O will measure a flux density

$$S = \frac{2\pi kT}{\lambda^2}\left(\frac{r}{D}\right)^2 \text{ w/m}^2\text{/cps.} \qquad (3\text{-}2)$$

Radio astronomers often express Eq. 3-2 in terms of the so-called *brightness* b of the source, where b is equal to the received flux density divided by the solid angle Ω subtended by the source. That is, $b \equiv S/\Omega$. If A is the cross-sectional area of the body (as seen from O), then by the definition of a solid angle $\Omega \equiv A/D^2 = \pi r^2/D^2$ steradian, and we can rewrite Eq. 3-2 as

$$b = \frac{2kT}{\lambda^2} \text{ w/m}^2\text{/cps/steradian.} \qquad (3\text{-}3)$$

Notice that b does not depend on the distance of the source, since both S and Ω vary as $1/D^2$. The concept of brightness is especially useful for extended sources resolved by the radio telescope, for then Ω is defined by the beamwidth of the instrument, rather than by the source, and it is possible to map the distribution of brightness over the source. Notice also in Eqs. 3-1 through 3-3 that the radiant energy falls off as $1/\lambda^2$. This means that the flux received at a wavelength of 1 cm is 10,000 times greater than that received at a wavelength of 1 m. No wonder the study of the thermal emission of the planets has been carried out in the microwave region!

Wein's Displacement Law. If a piece of iron is thrust into a flame, the metal first begins to glow dull red. Then, as its temperature rises, the iron changes from orange to yellow and finally it becomes white. If at each of these stages we could plot a radiation curve like that of Fig. 3-1 we would find that the peak of the curve shifts toward shorter wavelengths as the temperature of the iron increases. The actual relationship between the temperature and the wavelength λ_m of the peak is remarkably simple:

$$\lambda_m T = 2.897 \times 10^{-3} \qquad (3\text{-}4)$$

where λ_m is measured in meters and T is in degrees Kelvin. This equation, which is known as the Wein Displacement Law, states that λ_m is inversely proportional to the temperature of the radiating surface.

What does Eq. 3-4 tell us about the radiation curves of some familiar objects? If we make T equal to 6000° K, which is about the temperature of the surface of the sun, then $\lambda_m = 4.83 \times 10^{-7}$ m, which lies in the relatively narrow visible region of the spectrum. Since the peak of the radiation curve is rather flat, this means that all of the visible wavelengths are about equally represented and the sun appears whitish. If the reader will go outside on a clear night he will see other suns (stars) that appear red or orange and still others that are blue. Because the red stars are cooler than the sun their visible energy increases toward the red end of the spectrum. Conversely, the blue stars are much hotter than the sun, and the peaks of their radiation curves lie in the ultraviolet. The color of a star, like that of a piece of hot iron, tells us its temperature.

Averaged over the whole globe, the temperature of the earth is about 8° C or 281° K. Thus, the earth's radiation curve peaks near a wavelength of 1×10^{-5} m, which is deep in the infrared. Does this mean, then, that the earth radiates more energy than the sun at radio wavelengths? Not at all. The hotter body radiates more energy at *all* wavelengths than does the cooler body.

Graybodies. Most real substances radiate much less efficiently than a blackbody, but in many cases their radiation curves have the same general shape as the blackbody curve. The dotted line in Fig. 3-1 represents such a material, which is termed a "graybody." At each wavelength a graybody radiates a certain fraction e of the blackbody radiation, where e is called the "emissivity" of the material.

For some substances even the shape of the radiation curve is different from that of a blackbody. The extreme example of this is a gas at low pressure, where the spectrum consists of a number of individual sharp lines at various wavelengths. Radio astronomers often speak of the *brightness temperature* T_b of a source that may not be a true blackbody—nor perhaps even a thermal emitter at all. T_b is simply the absolute temperature of an equiv-

alent blackbody source that would have the same brightness as the actual source. It follows from Eq. 3-3 that

$$T_b = \frac{b\lambda^2}{2k}. \qquad (3\text{-}5)$$

While we believe that cosmic radio noise is emitted by spiraling electrons, rather than by a thermal process, we can say that the sky near the galactic center has a brightness temperature of 50,000° K at a wavelength of 15 m. This means that the radio brightness b of that part of the sky is the same *as if* we were looking at the surface of a blackbody at a temperature of 50,000° K.

THE QUIET SUN

We have pointed out before that it is beyond the objectives of this book to discuss solar radio astronomy, which is in itself an enormous field. However, as the largest and hottest body in the solar system the sun must certainly be a prime source of thermal radio emission, and it seems appropriate to mention it in the present chapter.

The reader may recall from Chapter 1 that near the beginning of the century several investigators attempted to detect solar radio waves, although one of them, Nordmann, made it clear that it was not simple thermal radiation which he was seeking. By coincidence these efforts were made at the time Planck was solving the riddle of blackbody radiation. Four decades were to elapse between these early, unsuccessful observations and Southworth's actual detection of thermal radio emission from the sun.

Ironically, Southworth felt that Planck's theory may well have discouraged solar radio studies during these intervening decades. He wrote, "The outlook for many years was not, however, promising. Calculations based on Planck's theory indicated that, even at the highest radio frequencies and with antennas of the highest directivity then available, the intensity would probably be far below the noise level prevailing in the local radio receiver." [1] Southworth, of course, was thinking of the state of the electronic art prior to World War II.

During the war, thanks to the efforts of thousands of scientists

involved in developing radar, the situation changed rapidly. Describing his own observations, Southworth wrote, "Early calculations had shown that with the best microwave receiving techniques available in 1942, the received power might well be hidden by noises arising in the first detector of the receiver itself, but it might still be observable. . . . After we had groomed a double-detection receiver to give a relatively low first-detector noise, it was almost natural that we should point the antenna at the sun. . . . We found, as expected, that the solar noise represented a small increase in the total noise output." Southworth added, a bit ruefully, "Because the War was on, it was difficult to find time to work on solar observations." [1]

At first Southworth believed that his measurements had confirmed the temperature of 6000° K which optical astronomers had established for the surface of the sun. Later a mistake was discovered in his calculations and the corrected radio temperature turned out to be 18,000° K. Soon radio astronomers found that the measured temperature of the sun depended very much on the wavelength at which the measurement was made. As the wavelength increased, the apparent temperature of the sun rose at an alarming rate.

Did this mean that the microwave energy was not really thermal radiation after all? The correct interpretation seems to be that at least in the case of the "quiet" sun—that is, the sun undisturbed by large sunspots, flares, or other activity—the microwave emission *is* actually thermal in origin. However, different radio wavelengths originate at different levels in the solar atmosphere. The shorter wavelengths come from a region just above the surface of the sun, which is at the relatively "cool" temperature of 10,000° K. Wavelengths of a meter or more, on the other hand, originate in the sun's outer atmosphere or "corona," where the temperature rises to 1,000,000° K. Thus each wavelength reflects the temperature of the atmospheric layer in which it has its origin. Although we can now say that we understand the thermal radiation of the sun rather well, no such reassuring statement can be made regarding the almost infinitely varied and complex phenomena associated with the disturbed or active sun!

THERMAL RADIATION FROM THE MOON

The moon is our nearest neighbor in space. A "mere" 240,000 miles away, it is nearly 400 times closer than the sun. The earth-moon system has sometimes been referred to as a "double planet" because the moon is far larger relative to its parent planet than is any other satellite in the solar system. Tidal friction has slowed the rotation of the moon until it now turns on its axis in just the same time that it circles the earth, thus always presenting the same face to us. By the same token, the lunar day is the same length as the lunar month—29½ of our days—and this is, of course, also the period in which the moon runs through the cycle of its phases.

Telescopically, the moon presents the forbidding scene that we see in Plate V. There are a number of relatively smooth dark areas known as "maria" or "seas," which are probably remnants of lava flows, but most of the surface is so densely pock-marked with huge craters that one often overlies another. Astronomers have argued long and heatedly over the origin of the craters. Some maintain that they are the result of volcanic eruptions, while others claim that they were created by the impact of great meteorites in the past. An occasional mountain peak or mountain range lends variety to the landscape, but the craters dominate the scene. Certainly the absence of any appreciable atmosphere has contributed much to the ruggedness of the moon's features, for there is no weather to erode away the peaks and fill the valleys.

What is the temperature of the lunar surface? With manned lunar exploration in the planning stage, this question is no longer merely academic: it has become a matter of practical importance. Let us now investigate the principles used in measuring the surface temperature of a distant and inaccessible astronomical body.

It may have occurred to the reader that Eq. 3-2 could rather easily be used for this purpose. All that seems to be necessary is to measure S at any convenient wavelength λ. But wait! If we go outside and look at the moon, all the light that we see is

reflected sunlight. Obviously we can learn nothing about the moon's temperature by measuring reflected sunlight. It is the thermal energy emitted by the moon itself that must be evaluated.

In the visible part of the spectrum the sun radiates strongly and the moon feebly. Fortunately, as we move into the infrared the situation begins to reverse itself, since the solar energy falls off rapidly while lunar emission increases. The solar radiation reflected from planetary surfaces is almost entirely confined to wavelengths *less* than 3 microns, whereas lunar or planetary emission itself is concentrated in the region *above* 3 microns, as we see in Fig. 3-3. Clearly, if we wish to determine the lunar temperature, we would do well to work at long wavelengths. For many years optical astronomers have done just this, isolating the

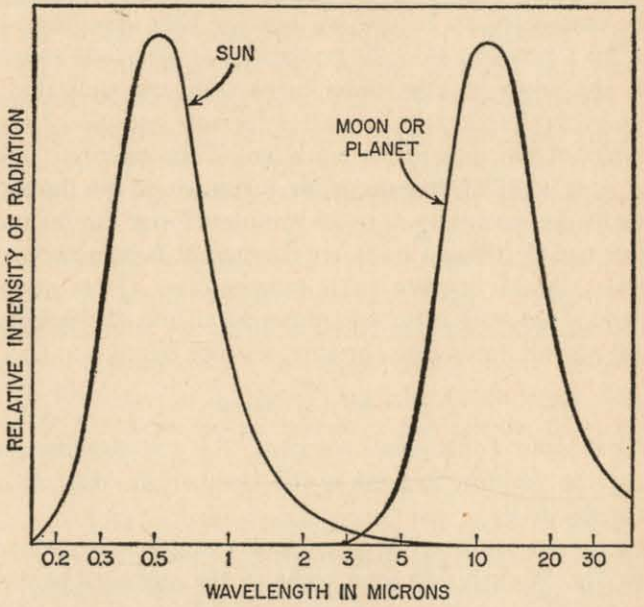


FIG. 3-3 Radiation curves for blackbodies at 6000° K (sun) and 273° K (moon or planet). It is assumed that the intensity of the solar radiation has been reduced to equality with that of the cooler body through reflection from a lunar or planetary surface. (After G. de Vaucouleurs, *Physics of the Planet Mars* [Faber and Faber Ltd., London, 1954], p. 161.)

desired spectral regions by means of filters. Their measurements of lunar energy are made by placing a delicate thermocouple at the focus of a large telescope that is directed at the moon. A blackbody or other standard source is used to calibrate the instrument, and the results must be corrected for residual solar radiation and for the absorption of the atmosphere.

By the time we get to radio wavelengths, the solar component is negligible and virtually all the energy received is true thermal radiation from the moon itself. It has been estimated that at centimeter wavelengths reflected solar rays could raise the observed temperature by no more than 1° C. Thus we see that the radio region is, at least in principle, an excellent one in which to measure lunar and planetary temperatures.

Just how do we go about making radio measurements of the moon's temperature? Before we answer that question, let us digress for a moment into the properties of electrical resistances. Those who work in electronics know only too well that a resistance generates electrical noise of its own because of the random thermal motions of its electrons. This internal "Johnson noise," as it is called, is responsible for much of the interference that limits the sensitivity of radio receivers. Since the fluctuations that give rise to Johnson noise are thermal, it is only natural that the noise should increase with temperature. If we connect a resistor to a properly matched transmission line, the noise power that the resistor feeds into the line is given by

$$P = kT\,(\Delta f) \text{ watts} \qquad (3\text{-}6)$$

where k is again Boltzmann's constant, T is the absolute temperature of the resistor, and Δf is the bandwidth over which we measure the noise.

If the resistor is placed in an enclosure that is at a temperature T_A (see Fig. 3-4a), it will soon come to the same temperature as its surroundings, and the power that it delivers to the transmission line will be characteristic of T_A; that is, $W = kT_A(\Delta f)$. Now—and this is the important point—if the resistor is replaced by an antenna that is also matched to the transmission line (Fig. 3-4b), the antenna will deliver exactly the same power as the resistor. In other words, the antenna feeds into the transmission

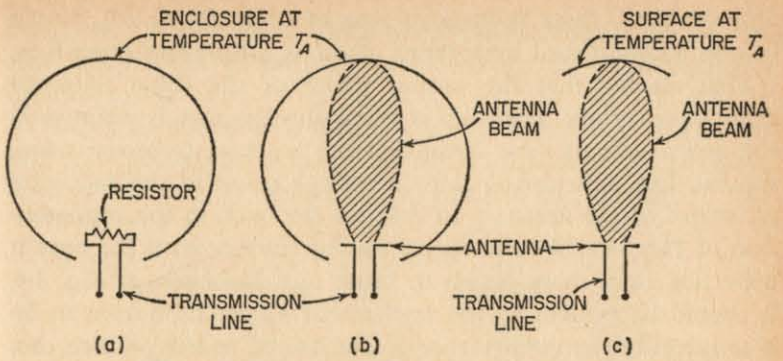


FIG. 3-4 The concept of antenna temperature.

line a thermal noise power that is characteristic of the temperature of the surface at which the antenna is "looking." In this situation it is customary to refer to the antenna as having an "antenna temperature" T_A. In practice, it is not actually necessary that the antenna be surrounded by an isothermal enclosure; we can remove all of the enclosure except the part that the antenna "sees" (Fig. 3-4c), and the antenna will continue to deliver the same noise power as before. It may be confusing to the reader that the *temperature of the antenna* and the *antenna temperature* T_A are now quite different things. The actual physical temperature of the antenna structure itself, like that of any other object, depends on its immediate environment, on whether the sun is shining, and so on. T_A, on the other hand, depends only on the temperature of whatever lies within the antenna beam, be it as remote as the moon.

Let us return, now, to the problem of measuring the moon's temperature. The apparent diameter of the moon is about ½°. In the centimeter-wavelength region it is not difficult to construct a radio telescope having a beamwidth considerably less than this, so that it is actually possible to scan the lunar disc section by section. In this case, as we have seen, the antenna temperature T_A will correspond to the average temperature T of the part of the lunar landscape that lies within the beam. In other words,

$$T = T_A. \qquad (3\text{-}7)$$

Our problem, then, reduces to that of determining T_A, which can be accomplished by a rather obvious calibration procedure.

First assume that the output meter of the radio telescope registers a certain deflection d when the antenna is pointed at the moon. Let us now disconnect the antenna from the transmission line and replace it by a resistor equal to the radiation resistance of the antenna, so that we are back to the configuration of Fig. 3-4a. We can then heat the resistor until the output deflection once more equals d. From our discussion of Fig. 3-4, it should be evident to the reader that all we now have to do is to measure the temperature of our heated resistor, which can, of course, be done by any of the usual means. This temperature corresponds to the antenna temperature T_A, which in turn is the temperature of the lunar surface. It seems rather remarkable that we can determine the temperature of the moon by measuring the temperature of a resistor in the laboratory!

We have omitted certain details that in practice can be a bit troublesome, such as corrections for atmospheric absorption, corrections for the actual antenna pattern, and so on. However, the principle of the measurement remains as simple as we have outlined it.

A good deal of time has been spent describing *how* one determines the temperature of the moon. What of the actual results? Thermal radiation from the moon was first detected in 1946 by the American scientists R. H. Dicke and R. Beringer, who used modified 1.25-cm radar equipment.[2] Later workers have made measurements at wavelengths ranging from 4 mm to 75 cm.

The most interesting results are those that show how the temperature at the center of the moon's disc changes with the phases of the moon. Let us jump a few years into the future and imagine that we have established a lunar base at this spot, perhaps in the small "sea" Sinus Medii. The earth will hang nearly fixed in our zenith, while once every 29 days the sun will rise above our eastern horizon, announcing the beginning of a lunar day that will last two earth-weeks. Naturally, we will expect it to be hottest near lunar noon, when the sun is almost directly overhead, at which time those back on earth will be enjoying a "full moon." Conversely, it ought to be coldest in

the middle of our lunar night when the sun is shining on the other side of the moon and earth-dwellers are experiencing a "new moon."

Infrared measurements made by E. Pettit and S. B. Nicholson with the 100-inch telescope at Mount Wilson show the expected variation. As Fig. 3-5 indicates, the infrared temperature at full

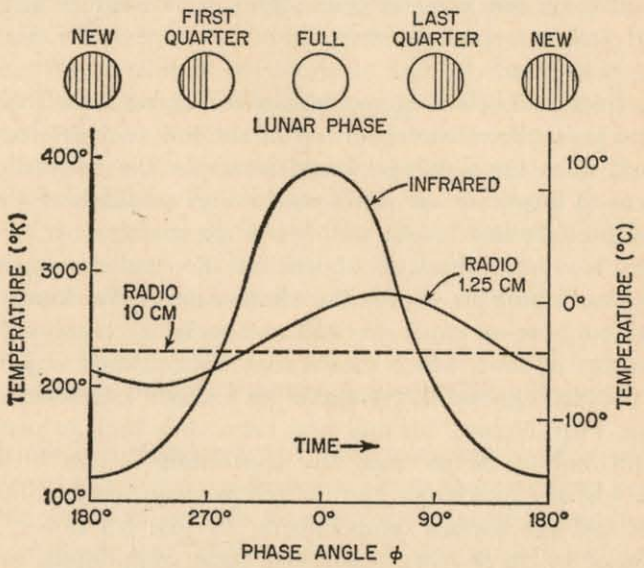


FIG. 3-5 Temperature of the center of the moon's disc throughout a lunar month. (Many writers take $\phi = 0$ when the moon is new, rather than full.) Infrared data after Pettit and Nicholson, 1.25-cm radio data from Piddington and Minnett, and 10-cm radio data from Koshchenko, Kuzmin, and Salomonovich.

moon (noon at our lunar base) reaches 390° K, or slightly above the normal boiling point of water. At new moon (midnight for our base) the temperature falls to 120° K, which is not far above the temperature of liquid air.

The radio data, some of which are plotted in Fig. 3-5, differ from the infrared results in two important respects. First, the range of temperature variation is not nearly so great, and second,

the maximum temperature occurs not at full moon, but several days later. What is the reason for these differences?

It seems almost certain that the lunar surface is opaque to infrared radiation, so that the thermal emission in this part of the spectrum must come entirely from a very thin surface layer. Infrared energy arising below this layer would be absorbed before it could escape. On the other hand, radio waves penetrate some distance into most nonmetallic materials before being absorbed and consequently they can also escape from this same depth. The result is that much of the radio energy probably comes from well below the moon's surface. If our lunar explorers were to lay a thermometer on top of the soil at their station, it is likely that the readings would resemble the infrared data, whereas to duplicate the radio results they would have to bury the bulb of the instrument well below the surface.

Thus it is not difficult to understand the smaller temperature variations found in the radio observations. We know from experience here on earth that soil and rocks are extremely poor conductors of heat, which means that underground regions are well shielded against the temperature changes occurring at the surface. Furthermore, because heat takes time both to penetrate the soil and to escape from any appreciable depth, it is easy to see why the maximum and minimum radio temperatures lag far behind the surface temperatures. As Fig. 3-5 shows, wavelengths of 10 cm or more apparently come from depths so great that the temperature variation is too small to measure.

Just how far beneath the lunar surface do the radio waves originate? Various investigators have given answers that differ considerably. However, it now seems likely that 3-cm waves come from a depth of about 20 cm while 1-cm radiation comes from only half as deep. If our lunar explorers were to burrow as little as one meter beneath the moon's surface, they would find a region of almost constant temperature, showing none of the wild fluctuations of the surface layer.

These conclusions are supported by the events that take place during a lunar eclipse, when the full moon passes into the shadow of the earth. The infrared data show that the lunar surface temperature plunges nearly 200° in an hour's time as the

moon enters the shadow and then, at the end of the eclipse, the temperature climbs just as quickly. These chameleon-like changes could only be occurring in a very thin surface "skin." The radio data, on the other hand, show no change at all during an eclipse, for the deeper layers of the lunar crust cannot react on such short notice.

Since the moon's temperature stabilizes at a much shallower depth than that of the earth, writers have argued that the moon must be covered by a material of exceptional insulating abilitiy. Pumice-like rock or a layer of fine dust have been suggested as suitable substances, and some investigators feel that a combination of the two is needed. Estimates of the depth of the dust layer have varied from fractions of a millimeter to tens of meters. (Perhaps our lunar explorers will need snowshoes!) The exploration of space has reached a point where radio astronomers are involved in a race against time if they wish to provide a better description of the moon's surface before they are "scooped" by the landing of lunar probes.

THE TEMPERATURES OF THE PLANETS

Method of Measurement. The temperature of a planet is measured by using the same principles as those we have described for the moon. In practice, however, there is one important difference. Whereas the moon subtends an angle of half a degree, the angles subtended by the planets range downward from one minute of arc. Thus far no radio telescope has been constructed with a beam narrow enough to be filled by the disc of a planet.

Suppose that the antenna beam covers an area of the sky of β square degrees while the area of the planetary disc is much smaller, say ω square degrees. (A "square degree" is, of course, the area contained in a square section of sky 1° on each side.) Eq. 3-7 now becomes

$$T_A = \frac{\omega}{\beta} T \tag{3-8}$$

where, as before, T_A is the antenna temperature and T is the brightness temperature of the surface of the planet. We see that the antenna temperature is lower by a factor ω/β than it would

be if the planet filled the beam. Since ω/β is generally very small, this is a serious problem and may easily lead to antenna temperatures so low that the planetary signals are masked by random fluctuations.

How are our measurements affected by cosmic radio noise from the sky background surrounding the planet? First, at centimeter wavelengths the brightness temperature of the sky is extremely low—not over a few degrees above absolute zero. Second, readings are taken by pointing the antenna ahead of the planet and allowing that body to "drift" through the beam as the earth rotates. In this way the planetary signal reveals itself as a "bump" in the background noise, so that what we are actually measuring is ΔT_A, the *increase* in antenna temperature due to the planet.

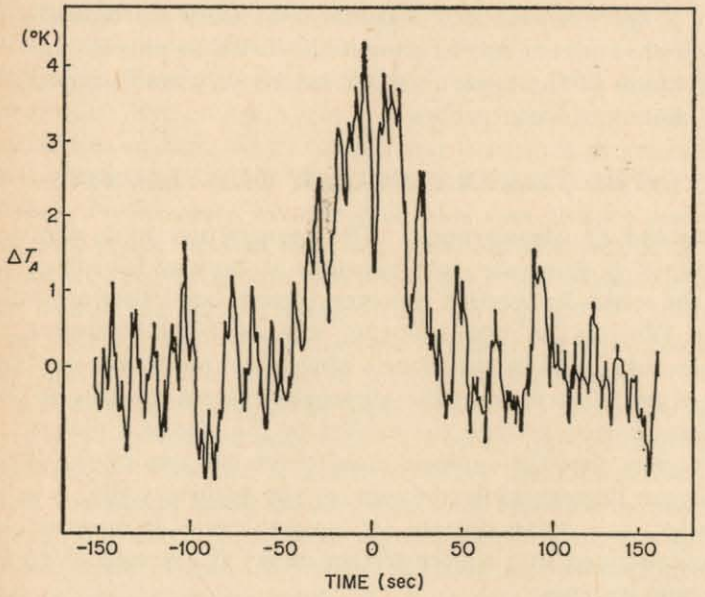


FIG. 3-6 Increase in antenna temperature as Venus drifts through the beam of the 50-foot radio telescope at the Naval Research Laboratory. The wavelength is 3.15 cm, and the erratic fluctuations are due to "noise" in the signal and in the receiver. (Reproduced from Mayer, McCullough, and Sloanaker, *Proc. Inst. Radio Engrs.* 46, 264 [1958] with the permission of the editors and the authors.)

(See Fig. 3-6.) The effects of random fluctuations are reduced by averaging many such scans. With the best modern receivers it is now possible to detect increases in antenna temperature of as little as 0.01° K.

The Solar System. This section is not intended for those of our readers who are familiar with the outlines of the solar system. It is included as an aid to those who are a bit rusty in their astronomy, since the sizes and distances of the planets are important ingredients of the radio-astronomical problem of measuring their temperatures.

Fig. 3-7 shows the orbits of the planets to scale. Curiously, it

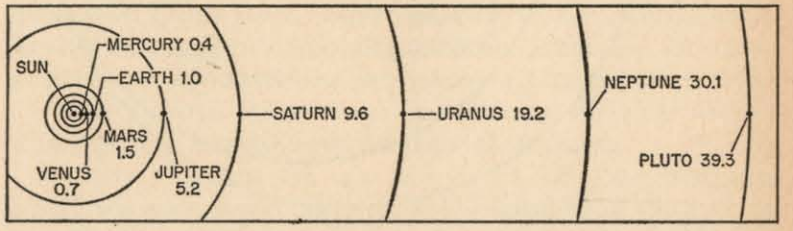


FIG. 3-7 The average distances of the planets from the sun. The numbers in the diagram give the distances in terms of the astronomical unit (A. U.), or average distance between the earth and the sun. One A. U. is 9.30×10^7 miles, or 1.50×10^8 km.

is the innermost planet and the outermost planet, Mercury and Pluto, whose orbits depart significantly from circles. The orbit of Pluto is so eccentric that at times that remote planet is actually closer to the sun than Neptune!

The real diameters of the planets are shown in Fig. 3-8 and their apparent diameters in Fig. 3-9. Jupiter, Saturn, Uranus, and Neptune form a distinct group of large planets of low density variously known as the "giant," "major," or "Jovian" planets. Since the remaining planets more nearly resemble the earth in size and density, they are called "terrestrial" planets.

Why do some of the planets in Fig. 3-9 show enormous variations in their apparent sizes, while others change but little? If the reader will study Fig. 3-7, he should have no difficulty in seeing that the relative distances of the *nearer* planets will vary

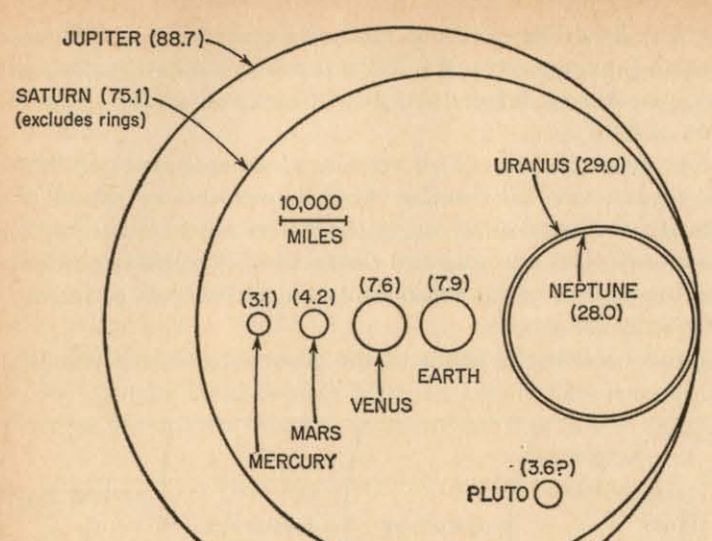


FIG. 3-8 The diameters of the planets. The numbers in the diagram give the diameters in thousands of miles. Pluto's diameter is highly uncertain.

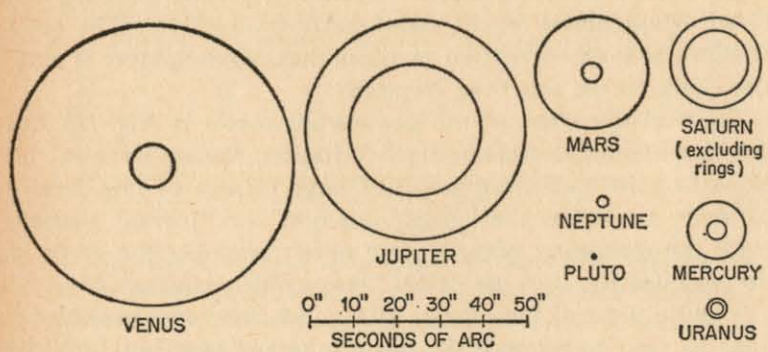


FIG. 3-9 Maximum and minimum apparent angular diameters of the planets as seen from the earth.

greatly as both they and the earth circle their respective orbits at different speeds. On the other hand, the relative distances of the outer planets remain more nearly fixed, since their orbits are of such great size compared to that of the earth. Needless to say, these phenomena are of considerable practical importance to both optical and radio observers.

Radio signals from a planet were first detected in 1955, when two young radio astronomers accidentally tuned in on the intense nonthermal radiation that Jupiter emits at decameter wavelengths. The following year scientists at the Naval Research Laboratory succeeded in measuring microwave radiation first from Venus, and then from Mars and Jupiter. In the intervening years microwave energy from Saturn and Mercury has been detected, so that we now have radio measurements of the five innermost planets—which is to say the five naked-eye planets known to the ancients. We shall now take up these planets one by one and see what has been learned from the radio observations.

Mercury. Circling the sun in only 88 days, the innermost planet was aptly named after the swift messenger of the gods. In fact, Mercury might well be described in terms of superlatives. Not only is it closest to the sun, it is also the smallest planet and possibly the densest. Because of its proximity to the sun it shares with Venus the distinction of being hottest, but curiously enough it is also perhaps the coldest! How can this be?

The tremendous tidal drag of the nearby sun has slowed Mercury's rotation until it keeps one face turned always toward the sun, while the other face looks perpetually into the cold of outer space. Because it is always near the sun in the sky and because it shows phases like those of the moon, the little planet is a difficult object to observe. Arid and virtually airless, Mercury resembles the moon both in superficial appearance and in physical condition. The most optimistic estimates of the planet's atmosphere limit it to a thousandth of the pressure of the earth's atmosphere, so that winds can play little part in carrying heat from the sunlit side to the dark side. Thus thermal conduction through the body of the planet is the only means of equalizing the temperatures of the two hemispheres, but as we have seen, planetary materials are notoriously bad conductors of heat—so

bad, in fact, that it is believed that what little heat is supplied to the dark face comes largely from subsurface radioactivity.

The infrared measurements of Pettit and Nicholson at Mount Wilson show that the surface temperature of Mercury at the subsolar point, or center of the sunlit hemisphere, is 613° K (340° C), which is above the melting point of lead! [3] No radiation has been detected from the dark side of the planet, which indicates that it cannot be far above absolute zero. An estimate based on a reasonable level of subsurface radioactivity suggests a temperature of 28° K, which is far colder than liquid air. The temperature extremes of Mercury make those of the moon seem mild.

In 1961 radio emission from Mercury was detected with the 85-foot radio telescope of the University of Michigan.[4] The average of many scans made at wavelengths of 3.45 cm and 3.75 cm gave an antenna temperature of 0.05° K. If one assumes that the temperature of the sunlit side of the planet is uniform, this value of ΔT_A gives a brightness temperature of 380° K for the entire disc.

It is more reasonable to suppose that the temperature will be highest at the subsolar point, and that it will fall as one moves away from that point and the altitude of the sun decreases. Theory indicates, in fact, that the temperature of a planetary surface should fall off as $(\cos \delta)^{1/4}$, where δ is the angular distance of the sun from the zenith. If we adopt this law, the radio temperature of the subsolar point turns out to be 1100° K, which is, of course, nearly 500° higher than the infrared result. Can this difference be due to the fact that the radio waves are coming from a few centimeters below the planet's surface? It seems more likely that the temperature simply fails to follow the $(\cos \delta)^{1/4}$ law, so that the edge of the disc is somewhat warmer and the center somewhat cooler than the theory would predict.

Venus. Of Venus it can truly be said that "it is a riddle wrapped in a mystery inside an enigma." Our lack of real knowledge is perhaps best indicated by the startling diversity of recent theories of the planet. Prominent astronomers have had the surface of Venus variously covered by arid deserts, by oceans and swamps, and even by a sea of oil! To know so little is especially tantalizing because Venus comes closer to the earth than any

other planet—so close that it has already been the target of several space probes. If we add to this the fact that of all the planets Venus most nearly resembles the earth in size and mass, it is easy to understand the current efforts to enlarge our meager store of data.

What are the reasons for our present ignorance? Most serious is the fact that Venus is continually shrouded in clouds so dense that no optical telescope can penetrate to its surface. At best the telescope shows vague shadings in the clouds, such as those that appear in Plate VI, and these are too ephemeral to permit even the rotational period of the planet to be determined. Furthermore, when Venus is at its closest it lies between the earth and the sun, and we see only its dark side. The illuminated hemisphere is fully presented to us when the planet is on the far side of the sun, and then its disc is discouragingly small for effective observation. Between these extremes, Venus shows phases like those of the moon.

Although optical techniques can probe the Venusian atmosphere only down to the level of the cloud-tops, all evidence indicates that Venus is surrounded by an extremely dense atmosphere. Recent estimates place the surface pressure at from 5 to 50 times that of our own atmosphere. The spectrograph shows that carbon dioxide is present in the enormous amount of two kilometer-atmospheres—that is, the CO_2 in the Venusian atmosphere *above the clouds* would form a layer 2 km deep if it were all at a pressure of one atmosphere. This is over 200 times the quantity of CO_2 in the *total* atmosphere of the earth! Attempts to detect oxygen and water vapor by means of spectrographs attached to large ground-based telescopes have been unsuccessful, although the reader should realize that these instruments are seriously handicapped by the masking effect of large quantities of oxygen and water vapor in the *earth's* atmosphere. In 1959 a team led by John Strong obtained spectra from a manned balloon at an altitude of 80,000 feet, which placed it above most of our atmosphere.[5] Although the results were not beyond dispute, they seemed to indicate the presence of a trace of water vapor in the upper atmosphere of Venus. (This experiment is an excellent illustration of why astronomers are anxious to orbit large tele-

scopes in satellite observatories, far above the limitations of the earth's blanket of air.)

Clearly, if we know the temperature of the Venusian surface we would have a vital clue to conditions there. Unfortunately, infrared waves are stopped by the clouds, and even the CO_2 of the upper atmosphere is somewhat opaque to these wavelengths. As we have indicated in Fig. 3-10, it seems likely that infrared penetrates no deeper than a region some 40 km *above* the clouds, so that the temperature of about −39° C (234° K) which is measured by the usual infrared methods applies only to this high-altitude layer of the atmosphere.

From observations of the spectrum of the CO_2 molecule near the visible part of the spectrum, J. W. Chamberlain and G. P.

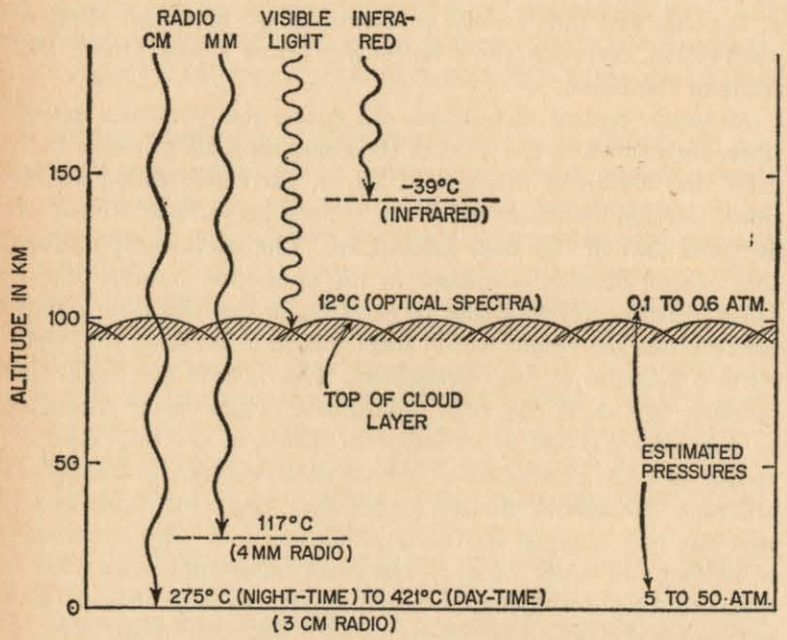


FIG. 3-10 Possible conditions near the surface of Venus. The figure indicates the methods used to measure the various temperatures and also suggests the depths to which different kinds of radiation might penetrate the Venusian atmosphere. Most of the values given in the figure are controversial and subject to revision.

Kuiper estimated that the temperature just above the clouds is 12° C.[6] While this is a bit closer to the surface of Venus, optical astronomers still could do little more than guess at the actual surface temperature itself. Many of the estimates fell in the vicinity of 100° C, raising a crucial question as to whether liquid water could exist on the planet. What could be done to obtain the missing information? The situation seemed to be "made to order" for radio techniques, since we know from experience here on earth that all but the very shortest radio waves readily pass through clouds.

Appropriately enough, Venus was the first planet to have its temperature measured at radio wavelengths. On May 2, 1956, 3.15-cm radiation was detected by C. H. Mayer and his colleagues at the Naval Research Laboratory in Washington, D. C.[7] Once more radio astronomers enjoyed an embarrassment of riches. The measured flux was far greater than had been expected, indicating a brightness temperature of about 600° K, or 327° C! If this was true thermal radiation, it implied that the surface of Venus was far hotter than anyone had imagined. It also seemed to end any hope of finding life on the planet that has often been described as the earth's twin. But was it really thermal radiation? Many optical astronomers were unable to believe that it was, and the radio observers had to admit that the excess flux might, at least in principle, have arisen from the motions of electrons in a Venusian ionosphere. However, to account for the observed energy this ionosphere would have to be so dense and so extensive as to seem rather improbable.

During the past six years radio energy from Venus has been studied at wavelengths ranging from 4 mm to 21 cm. From 3 cm to 21 cm the spectrum appears to be that of a blackbody at a temperature near 350° C. The evidence is strong that these wavelengths do emanate from the surface of the planet, and that the measured temperature, whether we like it or not, is that of the surface. At wavelengths below 2 cm the temperature decreases, falling to about 117° C at 4 mm. As Fig. 3-10 suggests, it is likely that the dense lower atmosphere stops very short radio waves some distance above the surface, so that the millimeter-wavelength temperatures are actually those of this lower atmosphere.

Most of the radio observations have been made near the time when Venus is closest to the earth, for the very good reason that the signal is 30 times stronger than it is when Venus is on the far side of the sun. The measured temperatures, therefore, are largely those of the dark hemisphere of the planet, and a question has existed as to whether there is a "phase effect"—that is, a significant difference between the temperatures of the daytime and nightime hemispheres. Recent 3.15-cm observations made at the Naval Research Laboratory indicate that the brightness temperature of Venus does vary with phase according to the law $T_b = 621° + 73 \cos(\phi - 12°)°$ K, where ϕ is the "phase angle," which has the same interpretation as in the lunar diagram of Fig. 3-5. This result implies that the sunlit hemisphere has an average brightness temperature 146° higher than that of the dark hemisphere, and that there is a 12° phase lag, similar to that of the moon, between zero (full) phase and the maximum temperature.

On the other hand, the infrared data show that there is little difference between daytime and nighttime temperatures in the upper atmosphere of Venus. Some have argued that this proves that the planet must rotate rapidly, but the truth of the matter is that the rotational period is completely unknown. Values ranging from 15 hours to 225 days have been "calculated" or "observed," and about all one can say is that the truth probably lies somewhere between. In 1956 J. D. Kraus believed that he had observed strong, nonthermal signals from Venus at a wavelength of 11 meters.[8] The radiation seemed to resemble the intermittent long-wavelength outbursts of Jupiter. Since the signals showed a periodicity of 22^h17^m, it was suggested that this was the long-sought rotation period of Venus. However, as Professor Kraus himself has pointed out, it now seems likely that the radiation that he observed was due to terrestrial interference.

How can we account for an average Venusian temperature which, on the absolute scale, is more than double that of the earth—621° K vs. 281° K? True, Venus is closer to the sun, but other things being equal, the absolute temperature of a planet should vary only as $1/\sqrt{r}$, where r is the mean distance of the body from the sun. For Venus, $r = 0.72$ A.U., while for the earth

$r = 1.00$ A.U. by definition. Thus the difference in distances could account for a temperature ratio of only 1.2 to 1. Clearly, other factors must be much more important.

It seems probable that the high Venusian surface temperature is the result of an exaggerated "greenhouse effect." Most of our readers will recall that a greenhouse is heated by a kind of "one-way" property of its glass roof. Light readily enters through the glass, but once it strikes a surface inside the greenhouse it is absorbed and converted into heat. Of course, the heated surface now emits thermal radiation, but almost entirely at wavelengths in the infrared to which the glass is quite opaque. The entering energy has been trapped inside the greenhouse; it got in, but it cannot escape. In the atmosphere of a planet, CO_2 and water vapor act much like the glass of a greenhouse; they are relatively transparent to the wavelengths that carry most of the energy of the incoming solar radiaton, but highly opaque to the infrared waves reradiated by the planet's surface.

C. Sagan has argued, on theoretical grounds, that the Venusian atmosphere must contain large amounts of water vapor, since CO_2 alone could not produce a sufficiently large greenhouse effect. It is indeed ironic if water, which has been eagerly sought on all the nearer planets as an indicator of possible life, should be the very agent that creates on Venus a temperature that seemingly rules out life as we know it.

An ingenious alternative to the greenhouse effect has been proposed by E. J. Öpik, who pictures the surface of Venus as a vast desert continually swept by fierce winds and dust storms. According to Öpik, the high temperature is produced by the *friction* of these winds. Thus we end as we began—with conflicting, unproved theories. Whatever the ultimate truth may be, there is little doubt that Venus is second only to Jupiter as the planet of greatest interest to radio astronomers.

Mars. Why has Mars excited far more interest than any other member of the sun's entourage? Why have more books been written about Mars than about all the other planets together? Probably the answer is no more complex than the simple fact that Mars is the only planet whose surface we can examine satisfactorily. Venus and the giant planets are forever shrouded in dense

clouds. We never find Mercury more than 28° from the sun, so that observations must be made either through the unsteady air near the horizon or in broad daylight. Pluto is so remote that it appears as a mere speck of light in the largest telescopes.

Mars is surrounded by a thin atmosphere which is reliably estimated to have a surface pressure about a tenth as great as that of the earth. Aside from infrequent local clouds or mists, and an occasional dust storm, this transparent atmosphere causes the optical astronomer little trouble. The spectrograph tells us that the Martian atmosphere, like that of Venus, contains large quantities of carbon dioxide, but the most assiduous searches for oxygen have been in vain.

A like failure to detect water vapor has long puzzled scientists, for the planet displays prominent white polar caps that behave like thin deposits of ice or snow. (See Plate VII.) Seasons on Mars resemble those on earth, since the axes of the two planets are tilted at almost the same angle to the planes of their orbits and the Martian day is only 37 minutes longer than our own. As the seasons progress, the polar caps shrink and expand just as one would expect from the melting and freezing of water. In April of 1963 astronomers H. Spinrad, G. Munch, and L. Kaplan finally succeeded in detecting the elusive water-vapor lines in spectra taken with the 100-inch telescope of the Mount Wilson Observatory. Their technique was based upon making observations at a time when Mars was receding from the earth at a velocity so high that the resulting Doppler effect shifted the Martian water-vapor lines out from under the much stronger, competing lines due to water in the earth's own atmosphere. Preliminary indications are that the amount of water vapor in the Martian atmosphere is so small that if all of it were to condense on the surface of the planet it would form a layer only 0.01 mm deep.

That the planet is arid is demonstrated by the fact that most of its surface is covered by a reddish desert. The conspicuous dark areas that relieve the monotony of the desert (see Plate VII) show seasonal changes in color and intensity, and most astronomers feel that the simplest and most natural explanation of these changes is to concede the presence of some form of plant life. What of the famous and controversial "canals" of which the

American astronomer Percival Lowell wrote in 1908, "These things . . . are artificial productions designed to the end they so beautifully serve. In the canals of the planet we are looking at the work of local intelligence now dominant on Mars."? [9] Today astronomers generally agree that there are details of the Martian surface that can appear as fine lines, but it is significant that the better the observing conditions are, the more natural these markings appear to be. Few would now subscribe to Lowell's thesis that the planet is crisscrossed by a network of artificial canals designed for the distribution and conservation of the water of the polar caps!

Infrared measurements indicate that the surface temperature on Mars ranges from a high of 33° C (306° K) at the subsolar point to −72° C in the polar regions. In September of 1956 Mayer and his colleagues at the Naval Research Laboratory trained their 50-foot radio telescope on Mars and made the first determination of the radio temperature of the planet.[10] Working at a wavelength of 3.15 cm, they obtained an average antenna temperature of 0.24° C, corresponding to a brightness temperature of −55° C or 218° K. The only other radio measurement was made in 1958 with the same antenna, but using a sensitive maser amplifier constructed by Columbia University scientists. This observation, made at a wavelength of 3.14 cm, yielded a temperature of −62° C.

How do the radio measurements compare with the infrared data? Since the planet is completely unresolved by the radio telescope, the radio temperature is an average for the whole disc. Attempts to reduce the infrared data to a similar average have produced estimates ranging from −13° C to −36° C. Apparently the radio temperatures are somewhat lower. As in the case of the moon, this could well be due to the fact that the infrared values refer to a thin surface layer, while the radio emission comes from some distance beneath the surface.

Astronauts landing on Mars would find the climate severe, but not intolerable if they were adequately clothed. They would also have an opportunity to investigate the only suggestion of life that man has yet found beyond his own planet.

Jupiter. Although most people know that Jupiter is the larg-

est of the planets, not everyone realizes that this one body alone contains 71 percent of the total mass of the planetary system. If we represent the mass of the earth by M_E, then the mass of Jupiter is 318 M_E, while the total mass of the remaining eight planets is only 130 M_E. As a consequence of its huge bulk, Jupiter possesses more angular momentum than the sun and all the other planets together, a fact that has created some difficulty for those who attempt to explain how the solar system got started.

If the mass of Jupiter seems surprisingly large, the reader should recall that the diameter of the planet is 11 times that of the earth. Since the volume of a sphere increases with the *cube* of its diameter, Jupiter actually would have a mass of over 1300 M_E if its density were the same as that of the earth! Evidently the larger planet is only about one-fourth as dense as our own.

In order to account for a density as small as that of Jupiter (1.35 gm/cm^3), it has been necessary to assume that the planet is composed almost entirely of the two lightest elements, hydrogen and helium, with perhaps a small core of heavier substances. Until well into the present century it was generally believed that the surface of Jupiter was hot enough to be faintly self-luminous, and the apparent low density of the planet was explained by assuming that the visible surface was merely the outer layer of an enormously deep atmosphere which concealed a solid body of relatively small size. In 1888 the well-known astronomer Sir Robert Ball pictured this theory in terms of an analogy with the earth:

> It seems likely that at some incredibly remote epoch all the oceans now reposing on the surface of the earth, and perhaps a considerable portion of its now solid crust, must have been in a state of vapour. . . . If all our oceans were transformed into vapour, our atmosphere, charged with mighty clouds, would have a bulk some hundreds of times greater than that which it has at present, and the size of the globe would be correspondingly swollen. Viewed from a distant planet, the cloud-laden atmosphere would seem to indicate the size of our globe, and its density would accordingly be concluded to be very much less that it is at present. . . . The discrepancy between the size and weight of Jupiter, as contrasted with our earth, would be completely removed if we supposed that Jupiter was at the present day a highly-heated body in the condition of our earth countless ages ago.[11]

This rather picturesque theory received a severe blow in 1934 when Rupert Wildt called attention to the fact that a planet cannot have an atmosphere of unlimited extent. At a certain depth the pressure of the atmosphere itself would cause gases to liquefy or even to solidify. How deep, then, *is* the atmosphere of Jupiter? Since the critical depth at which liquefaction takes place depends on the temperature and composition of the gases, as well as on the surface gravity of the planet, it is not possible to give an exact answer. Estimates have ranged as low as 100 kilometers, which would make the Jovian atmosphere even shallower than that of the earth!

Whatever the depth of the atmosphere, the telescope shows that it is filled with dense clouds of unknown composition, which completely hide whatever lies below. In spite of its huge size, the planet spins on its axis in less than ten hours, and this rapid rotation causes the clouds to stream in belts parallel to the equator, giving the planet the characteristic banded appearance that we see in Plate VIII. Many devoted observers have given years of their lives to studying this changing panorama of clouds, and in the next chapter we shall have occasion to refer to the history and behavior of certain of the cloud markings. The spectrograph shows that fairly large quantities of the noxious gases ammonia and methane are present in Jupiter's atmosphere above the clouds. However, the bulk of the atmosphere is probably composed of hydrogen and helium, with the latter predominating.

To summarize, Jupiter appears to be a vast body consisting largely of hydrogen and helium, the two most common elements in the universe. It is surrounded by an atmosphere of the same gases which, at a relatively shallow depth, condenses under its own weight into a liquid sea. Whether the planet is solid or fluid at still greater depths depends upon the unknown behavior of matter at enormous pressures ranging up to 10^8 atmospheres. A detailed model of Jupiter's interior probably must await progress in high-pressure solid state physics. Some theorists believe that Jupiter is almost as large as it is possible for a planet to be. According to this point of view, if Jupiter were somewhat more massive, it would have collapsed under its own gravity to form a star of the so-called "white dwarf" variety, rather than a planet.

So far we have said nothing about the temperature of Jupiter. Microwave energy from the great planet was initially detected at a wavelength of 3.15 cm by scientists of the Naval Research Laboratory.[10] Their first measurements, made in May of 1956, indicated that the brightness temperature of Jupiter was 140° K, or −133° C. Since infrared data had given results nearly identical with this radio temperature, there seemed to be no cause for concern. During the next two years the radio measurement was repeated by several laboratories, but always at wavelengths near 3 cm, and none of the temperatures that were obtained differed very significantly from the original figure of 140° K.

The first real surprise was provided by E. F. McClain and R. M. Sloanaker of the Naval Research Laboratory.[12] Using NRL's new 84-foot radio telescope during the summer of 1958, the two men made 60 observations at a wavelength of 10.3 cm. The individual temperature values ranged from 390° to 860° K, with an average of 580° K! What could this unexpected jump in temperature between the wavelengths of 3 cm and 10 cm mean? It gave rise to immediate suspicion that much of the 10-cm radiation might not, in fact, be thermal in origin. Of course, other radio astronomers were immediately stimulated to investigate the mystery by making observations at still longer wavelengths, but we shall have to wait until the next chapter to pursue this story to its end.

Saturn. It is useful to think of Saturn as a smaller, slightly colder "Jupiter," since the two bodies are believed to be similar in constitution. However, the average density of Saturn is not only much lower than that of Jupiter; it is even lower than the density of water, so that the planet, at least in principle, would float!

Like Jupiter, Saturn is enveloped in opaque clouds that stream in belts parallel to the equator as a result of the rapid rotation of the planet. If we compare Plates VIII and IX, we see that the belts of Saturn are more regular than those of Jupiter and that the planet as a whole appears more *tranquil.* Spots and other eruptions are so infrequent that any conspicuous marking is eagerly seized upon as an opportunity to determine the rotational period of the corresponding belt or zone.

What of the famous—and as far as we know unique—system of rings that surrounds Saturn? Although the rings are a striking sight in the telescope, their total mass is negligible compared with the planet itself. In 1857 the noted physicist Clerk Maxwell won a prize offered by the University of Cambridge by proving that neither a solid nor a fluid ring could form a stable configuration. Maxwell concluded that ". . . the only system of rings which can exist is one composed of an indefinite number of unconnected particles, revolving round the planet with different velocities according to their respective distances." [13] In other words, each particle should be thought of as a tiny satellite in its own orbit about Saturn's equator. So rigidly are the orbits confined to the equatorial plane that recently the thickness of the rings has been estimated by M. S. Babrov as roughly 1 km. Since the outer diameter of the ring system is 278,000 km, this means that relative to its longer dimension a page of this book is 80 times as thick as the rings!

How did this incredible system of rings originate? Saturn now has nine moons, and it is conceivable that once there was a tenth which strayed too close to the parent planet and was destroyed by gravitational forces. The rings would represent the debris of the lost satellite. However, optical measurements indicate that the material of the rings is finely divided and it is difficult to imagine a moon being broken up into such tiny fragments. It seems more likely that the rings represent a *potential* satellite that somehow failed to condense out of the primordial material from which the solar system was formed.

Infrared measurements by Pettit and others indicate that the disc of Saturn is at a temperature near 125° K, or −148° C. Presumably this value refers to a region near the top of the cloud layer. Although Saturn is only about 20° colder than Jupiter, there is less ammonia in the atmosphere of the ringed planet. This 20° temperature drop occurs in just the range where ammonia freezes out of the atmosphere at a rapid rate.

In 1957 F. D. Drake and H. I. Ewen detected 3.75-cm radio waves from Saturn with a parabolic antenna only 28 feet in diameter. The antenna temperature was a mere 0.04° K, and only a crude estimate of the microwave temperature of the planet

could be made. More recently radio astronomers of the University of Michigan have repeated the measurement with an 85-foot radio telescope and ruby maser amplifier operating at a wavelength of 3.4 cm.[14] With this larger antenna ΔT_A was near 0.1° K, and the average of 14 scans of Saturn gave a brightness temperature of 106° K. Although this value is somewhat lower than the infrared result, the difference is less than the possible errors in the two measurements.

The radio temperature computation was based on the assumption that the rings contributed nothing to the microwave emission. If we were to assume that the rings *did* emit a measurable 3.4-cm signal, then the computed temperature would be still lower, since we would in effect be attributing the same amount of energy (the received flux) to a much larger area. Because this would *increase* the discrepancy between the radio temperature and the infrared temperature, it might be regarded as a kind of indirect indication that the rings do not emit much microwave energy. This could be due either to a very low temperature or to the fact that the ring particles are extremely small and far apart. It is not unlikely that both conditions exist.

THE FUTURE OF THERMAL MEASUREMENTS

What is the future of thermal radio astronomy? What new worlds lie ahead to be conquered by the great parabolic radio telescopes? Beyond Saturn are the remaining giant planets, Uranus and Neptune, forming the solar system's second set of twins. Like the earth and Venus, these bodies are nearly identical in size, each being about one-third the diameter of Jupiter. (See Fig. 3-8.) Each is also somewhat denser than Jupiter, suggesting that they may be composed of a mixture that contains less hydrogen and more helium than does the larger planet. Because of the remoteness of these two planets, little detail can be seen in the telescope, but what evidence there is hints at a superficial resemblance to Jupiter and Saturn.

We would expect Uranus and Neptune to be frigid bodies because of their great distance from the sun. The spectrograph shows that the atmospheres of the two planets are rich in methane, but ammonia seems to be frozen out completely. Infrared measurements give the temperature of Uranus as 90° K, or −183° C, which is within a few degrees of the boiling point of liquid air. Neptune is probably about 15° colder, although its temperature has never been measured directly.

Marking the frontier of the solar system, Pluto remains a planet of mystery, its tiny disc distinguishable from a star-like point by only two or three of the world's greatest telescopes. Using the 200-inch telescope of the Mt. Palomar Observatory, Kuiper has estimated that the diameter of Pluto is only 46 percent of that of the earth. Yet the gravitational pull of Pluto on other planets indicates that it is nearly as massive as the earth. If we were to accept these conclusions at face value, the density of Pluto would exceed 50 gm/cm³, a figure that few are inclined to believe. The temperature of this remote body can only be guessed at, but it is probably near 45° K. Because of the eccentricity of its orbit, Pluto is drawing nearer to the earth, and between the years 1969 and 2009 it will actually be less distant than Neptune. Perhaps a concerted attack by radio and optical techniques near the time of closest approach in 1989 will unravel some of the mysteries.

What are the chances of making radio measurements of the temperatures of these three outer planets? We can put Eq. 3-2 in a more convenient form by noting that $r/D = \theta/2$, where θ is the angle in radians subtended by the planet in Fig. 3-2:

$$S = \frac{2\pi kT}{\lambda^2}\left(\frac{\theta}{2}\right)^2 \text{ w/m}^2\text{/cps.}$$

Combining the numerical constants and recalling that one second of arc equals 4.86×10^{-6} radians, we obtain

$$S = 5.14 \times 10^{-34}\frac{T}{\lambda^2}\theta_s^2 \text{ w/m}^2\text{/cps} \qquad (3\text{-}9)$$

where θ_s is the apparent angular diameter of the planet in seconds of arc, which is the unit in which such diameters are almost always tabulated.

We have made use of Eq. 3-9 to compute the flux that might be expected from each planet when it is at its least distance from

the earth, and the results are shown in Fig. 3-11. The radio temperatures were used in the calculations in those cases where the value was already available. Also shown are curves for the two largest satellites in the solar system, Jupiter's Ganymede and Saturn's Titan.

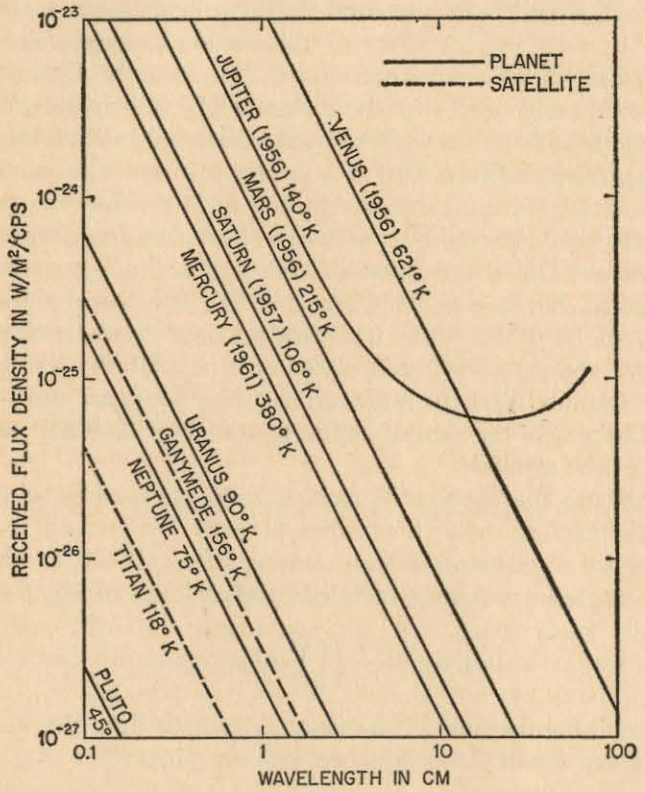


FIG. 3-11 Maximum microwave flux density for each planet and for two satellites. The upturned tail on the Jupiter curve is due to nonthermal emission. For the five inner planets, numbers in parentheses indicate the date of actual observation. All curves apply to minimum distance of the body from the earth except for Mercury, where the curve applies to maximum angular distance of the planet from the sun, which is the only condition for which satisfactory observation is now possible. (Suggested by a drawing prepared by C. H. Mayer.)

It is perhaps not surprising that the microwave detection of the planets has proceeded in just the order of the instrumental sensitivity required (that is, from right to left in Fig. 3-11). When we note that it took four years to bridge the relatively small gap between Saturn and Mercury on the diagram, the jump to Uranus begins to look formidable, and we see that it will take more than a tenfold increase in sensitivity at any one wavelength to accomplish the feat.

For a given planet it is possible to gain flux rapidly by going to shorter wavelengths, but this requires antenna surfaces of greater and greater precision, as we have observed in Chapter 2, and the engineering problems soon become insuperable. The 50-foot reflector of the Naval Research Laboratory and the 72-foot reflector of the Lebedev Physical Institute in Russia are the outstanding high-precision paraboloids in use today, with the latter having operated successfully at wavelengths as short as 4 mm. A 140-foot, centimeter-wave antenna is under construction at the National Radio Astronomy Observatory in West Virginia. It is believed that this instrument will bring Uranus within reach, but probably not Neptune, although continuing improvements in receiving equipment might alter the situation. The larger satellites of the Jovian planets will probably be observed by radio telescopes before distant Pluto is conquered.

Does the future of thermal radio astronomy lie, then, entirely in reaching out for bodies as yet undetected? Not at all! It is at least as important to refine the relatively crude measurements that have already been made. Better observations of the nearer planets may solve such outstanding astronomical mysteries as the rotational period of Venus, the physical nature of that enigmatic planet's surface, and the composition of Saturn's rings. The work of the thermal radio astronomer has scarcely begun!

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4 *The Radio Spectrum of Jupiter*

The noted scientist Vannevar Bush once said that there is no more thrilling experience for a man than to be able to say that he has learned something which no other person in the world

ever knew before him. This remark was quoted by the young astronomer K. L. Franklin in describing his emotions when he and Bernard Burke accidentally discovered that Jupiter, the largest of the planets, was occasionally broadcasting powerful radio waves.

The time was early 1955, and the two men were engaged in testing a large radio interferometer which the Carnegie Institution had just erected near Washington, D. C. Of a type known as a "Mills Cross," the new array was designed for mapping cosmic radio noise and discrete sources at a frequency of 22.2 Mc/sec. In a fascinating account of the events leading up to their discovery, Franklin recalled that "At times the records exhibited a feature characteristic of interference. . . . I recall saying once that we would have to investigate the origin of that interference some day. We joked that it was probably due to the faulty ignition of some farm hand returning from a date." [1]

When Burke finally compared a large number of records he was startled to find that the "interference" always occurred at about the same sidereal time—that is, some four minutes earlier each night by ordinary clocks. This was a strong hint that the noise was celestial in origin, but a search of a star atlas failed to disclose any likely object that would have been in the antenna beam at the correct times.

Franklin's account continues, "The late Howard Tatel . . . somewhat facetiously suggested to Burke and me that our source might be Jupiter. We were amused at the preposterous nature of this remark, and for an argument against it I looked up Jupiter's position in the *American Ephemeris and Nautical Almanac.* I was surprised to find that Jupiter was just about in the right place. . . . As twilight came and went we were delighted by a fine, clear sky. Burke asked me what one exceptionally bright object was, almost on the meridian. We had a good laugh when I told him it was Jupiter."

The following day Franklin made a plot in celestial coordinates of the positions of all the "interference" events. He then began to plot the position of Jupiter on the same diagram. "As I plotted each point, Burke, who was watching over my left shoulder, would utter a gasp of amazement. Each point appeared

right between the boundary lines representing the beginning and end of each event. The meaning was exquisitely clear: These events were recorded only when the planet Jupiter was in the confines of the narrow principal beam of the Mills Cross. . . . The source of the intermittent radiation was definitely associated with Jupiter!"

This totally unexpected discovery was the first recognition of radio frequency energy from a planet. Eight years later, despite the great strides that have been made in radio astronomy, Jupiter still appears to be unique among the planets as a radio transmitter. Only the sun itself rivals the giant planet as a source of powerful outbursts in the short-wave bands of the radio spectrum, and it is probably safe to say that Jupiter is being studied more intensively at the present time than in any other period in history.

THE LOCALIZED SOURCES

Pre-Discovery Observations. Astronomical history relates that the planets Uranus and Neptune were mapped as stars many times before their true nature was recognized. In fact, one astronomer had the questionable distinction of recording Uranus as a star twelve times before Herschel at last "discovered" the new planet in 1781! In a similar way, it turned out that radio signals from Jupiter had been recorded long before they were finally identified by Burke and Franklin.

The two Carnegie scientists themselves found that they had unwittingly recorded a strong Jupiter outburst a year before their discovery, but the most exciting "find" was made by the Australian radio astronomer C. A. Shain. As soon as he learned of the detection of Jovian radio outbursts, Shain re-examined an extensive series of old records that had been taken at a frequency of 18.3 Mc/sec in 1950 and 1951. Although these records had been made for the purpose of mapping the cosmic radio noise, no less than 61 of them proved to contain disturbances which now indicated by their positions that they were due to Jupiter.[2] As in the case of Burke and Franklin, the signals originally had been dismissed as being due to terrestrial interference.

While Shain had missed his opportunity to become the founder of planetary radio astronomy, he immediately had at his disposal a large body of data that antedated the actual discovery by nearly five years, and he proceeded to make good use of his windfall. Within a short time he was able to show that the radio energy came from a localized area or "source" on the disc of Jupiter, rather than from the planet as a whole. He furthermore noted that this source could be heard only when it was near the center of the visible disc—that is, when it was more or less "aimed" toward the earth.

How was the Australian able to make these pronouncements, when no decameter-wavelength radio telescope then in existence had nearly enough resolving power to make a point-by-point analysis of Jupiter's disc? In order to demonstrate the presence of his localized source, Shain adapted a technique that had long been used by optical astronomers interested in keeping track of the visual features of the planet; he employed an arbitrary system of Jovian *longitudes.*

At first glance, it may not seem quite feasible to ascribe a longitude system to a body that, like Jupiter, is perpetually hidden in clouds, so that it lacks any permanent landmarks. (Where, the reader may ask, is Greenwich?) In practice, however, such a longitude system requires little more imagination than visualizing meridians inscribed upon the trackless oceans of the earth. One merely postulates that 0° of longitude is at the center of Jupiter's disc at some given instant, and that the system thereafter continues to rotate forever at constant speed. During each succeeding rotation of the planet, the longitude of the "central meridian"—that is, the line bisecting the visible disc—increases steadily from 0° to 360°, and by simple calculation one may determine this longitude at any moment. Thus, the longitude of a marking can be established merely by noting the time at which it crosses the central meridian.

It is not difficult to see that if a marking rotates more rapidly than the longitude system, its longitude will continually decrease, while if it rotates more slowly its longitude will increase. The "drift" of the feature with respect to the longitude system is thus a measure of its rate of rotation. In keeping track of

markings it obviously is convenient to eliminate this drift—that is, to define a longitude system which rotates as nearly as possible at the rate of the features of interest, so that the longitudes of those features remain constant. Here the observer of Jupiter is faced with a dilemma. The rapid rotation of the great planet has drawn the clouds into belts parallel to the equator (see Plate VIII), and different belts rotate at different speeds; in fact there are adjacent belts that move past each other with relative velocities as high as 250 miles per hour! Because the greatest difference occurs between the clouds within 10° of the equator and those in higher latitudes, optical astronomers long ago were led to define two separate longitude systems. "System I" rotates in $9^h50^m30^s.003$ and is employed for the equatorial zone. "System II," with a period of $9^h55^m40^s.632$, is used for the rest of the planet.*

Shain was able to demonstrate the existence of a local radio source on Jupiter by the simple device of plotting the number of times signals were received when various longitudes were on the central meridian of the planet. As we see in Fig. 4-1, the data were divided into 5° intervals of longitude for convenience in handling; a graph in which the data are grouped in this fashion is called a "histogram." It is obvious that radiation was detected almost entirely when one particular face of Jupiter was turned toward the earth. In Shain's own words, "This figure shows that for a band of longitudes centered on 67° and extending from about 0° to 135°, the frequency of occurrence was much greater than outside this band. This suggests an origin in a very localized source on Jupiter." [2]

In searching for a suitable longitude system, the Australian tried both System I and System II. The period of the radio data seemed almost to match that of System II, but over an interval of several weeks a slight drift was noticeable, which led him to adopt the somewhat shorter period of $9^h55^m13^s$ for the radio source. Shain had demonstrated the existence of a local radio source merely by noting the times at which radiation had been

* The *American Ephemeris and Nautical Almanac* (prepared annually by the U. S. Naval Observatory and published by the Government Printing Office) contains tables from which the longitude of the central meridian can easily be determined for either system at any desired time.

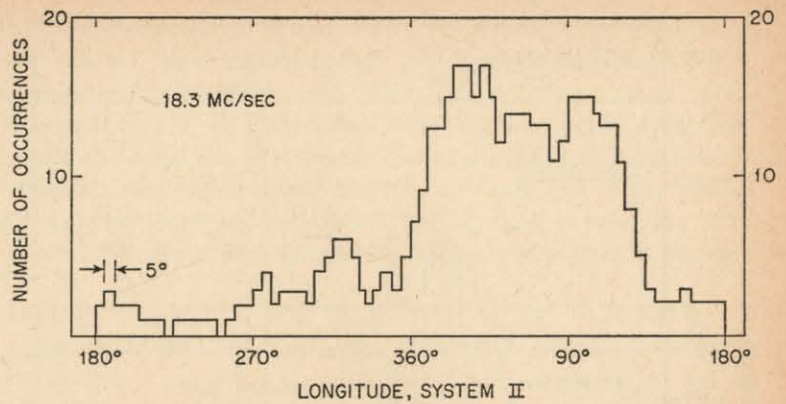


FIG. 4-1 C. A. Shain's histogram of the 1951 prediscovery radio observations of Jupiter. The data cover the period from August 15 to October 2. (After C. A. Shain, *Nature* 176, 837 [1955].)

received, but the reader should understand that this kind of analysis gives no information whatever about the *latitude* of the source.

Recent Observations. Radio astronomy suffered a severe loss when an untimely death removed Shain from the ranks of the Jupiter observers. In recent years extensive decameter radio observations of Jupiter have been carried on by the authors and their students, by Professors Harlan Smith and James Douglas of Yale University, and by Dr. James Warwick of the High Altitude Observatory at Boulder, Colorado. These observations have amply confirmed Shain's conclusion that the radiation is localized on the disc of Jupiter. They have also shown that there is more than one radio source.

In Fig. 4-2 we see three histograms constructed from the 1960 data of the University of Florida Radio Observatory.[3] These histograms differ slightly from Shain's in that the vertical axis represents the *probability* of receiving radiation, rather than a simple count of the number of occurrences. The probability can best be thought of as the fraction of time that signals were detected when a given longitude zone was on the central meridian, and it has the advantage that it should remain more or less

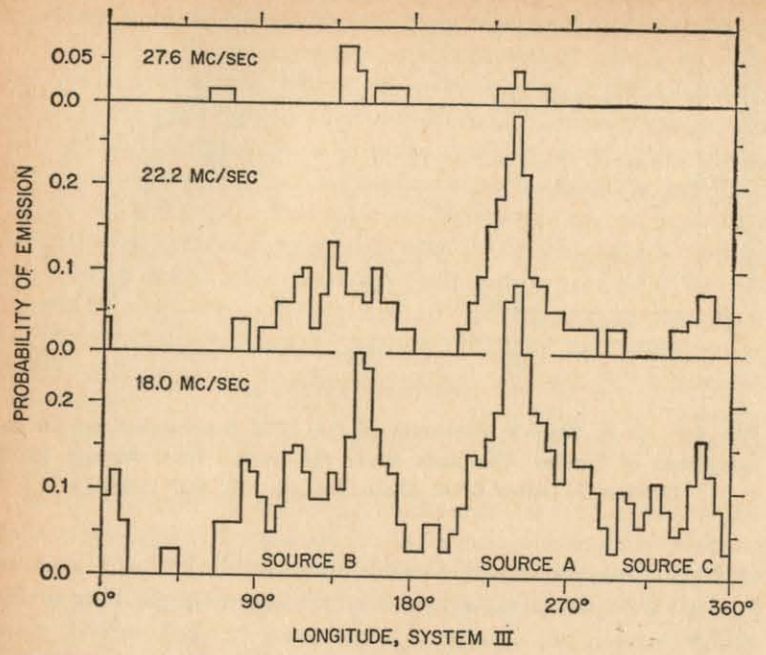


FIG. 4-2 Histograms of Jovian radio noise at three frequencies. Based on observations of the University of Florida Radio Observatory from December 26, 1959, to May, 21, 1960. (After T. D. Carr, A. G. Smith, H. Bollhagen, N. E Chatterton, and N. F. Six, *Astrophys. J.* 134, 108 [1961].)

constant, whereas the number of occurrences obviously depends on how long observations are carried on.

The reader can see that the histograms of Fig. 4-2 show more than one peak and that the pattern tends to repeat itself for data recorded at different frequencies. What about the stability of the pattern over long periods of time? The same pattern seems to recur year after year. In particular, the "sources" *A*, *B*, and *C* generally appear as features of any histogram that is based upon enough data to be trustworthy. One can even see these peaks in Shain's 1951 histogram. Fig. 4-2 also shows that the Jovian radio sources fall far short of emitting continuously. Even the principal source *A* does not exceed a probability of 0.34, which indicates

that signals were received only one-third of the time when this source was on the central meridian. Evidently the activity of the sources is highly sporadic.

Recently Dr. N. F. Six of the Florida group made a careful study of the available histograms, using an electronic computer to combine data taken over a number of years and to "smooth" the results by averaging each point with the points on either side of it. Fig. 4-3 shows Six's smoothed histogram for the 18 Mc/sec

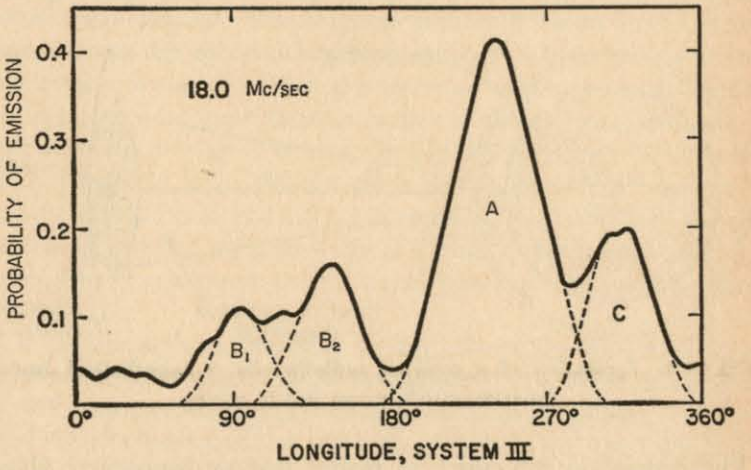


FIG. 4-3 A smoothed and averaged histogram showing probable bifurcation of one of the radio sources. (A. G. Smith, T. D. Carr, and N. F. Six, *La Physique des Planetes* [Institut d'Astrophysique, Cointe-Sclessin, Belgium, 1963], p. 544.)

data, which are the most numerous and therefore the most reliable. Sources *A*, *B*, and *C* appear unmistakably, and there is a strong suggestion that *B* is actually a pair of sources not quite resolved. This histogram perhaps gives as good a representation of the Jovian decameter sources as is possible at the present time. It is clearly the main task of any successful theory of the radiation to explain the presence of these sources and to account for their geographical distribution.

A Jovian Ionosphere. If you have followed the preceding discussion attentively, you may be asking a question that puzzled

Shain. Why doesn't each peak of the histograms spread over a full 180° of longitude? Certainly one would expect each source to be heard as long as it is anywhere on the visible hemisphere of Jupiter.

Shain concluded that his source must have a *directional* property, with the radiation confined to a relatively narrow vertical beam rather than being emitted in all directions. In this event the source would be heard only when it was near the center of the disc, with the beam "aimed" toward the earth. (See Fig. 4-4.)

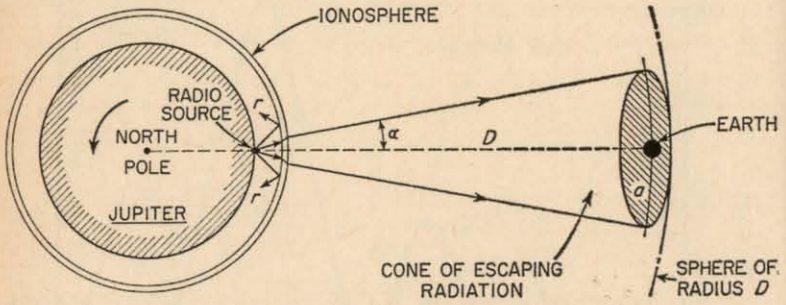


FIG. 4-4 Formation of a cone of radiation by a hypothetical Jovian ionosphere (distances not to scale).

The Australian was quick to realize that an *ionosphere* above the source would restrict the radiation to a vertical cone in just the manner desired.

The lowest frequency that is capable of penetrating an ionospheric layer is known as the "critical frequency" f_o of that layer. If there is a source of frequency f below the layer, radiation from the source can escape only into a cone whose half-angle α is given by

$$\cos \alpha = f_o/f. \qquad (4\text{-}1)$$

Rays that lie outside this cone, such as those marked r in Fig. 4-4, are totally reflected and cannot reach an observer above the ionosphere.

Unfortunately for Shain's attractive theory of a Jovian ionosphere, as data are taken at higher and higher frequencies the peaks on the histograms tend to grow narrower and narrower;

the reader can verify this for himself by looking at Fig. 4-2. Eq. 4-1, on the other hand, indicates that as the frequency f increases, the cone angle α should also increase, which would lead to *broader* histogram peaks! Since theory and experiment disagree, the theory must be abandoned, at least for the present.

If the simple ionospheric model of Fig. 4-4 *were* correct, one could readily estimate the electron density in the Jovian ionosphere. For a source near Jupiter's equator, α would be equal to the half-width of the histogram peak, so that f_o could be computed from Eq. 4-1. The electron density N could then be obtained from the relationship $N = \pi m f_o^2/e^2$, where m and e are the mass and the charge of the electron, respectively. If we are willing to ignore the difficulties with the theory, what sort of result does this give us? The peaks in Fig. 4-3 are roughly 70° wide, so that $\alpha \cong 35°$. This yields a value of $f_o = 15$ Mc/sec and leads to an electron density of 2.7×10^6 electrons per cubic centimeter. About all one can say is that this is similar to the maximum electron density measured in the usual layers of the earth's ionosphere.

If the ionosphere theory is wrong, what then *does* limit the cone of radiation from the Jovian sources? At present this is one of the unsolved mysteries of the great planet, another enigma that must be explained by any successful theory of the radio outbursts.

The Radio Rotation Period. We have seen that Shain was led to adopt a rotational period for the radio sources that was 28 seconds shorter than the System II period used by optical astronomers. His figure, however, based on less than two months of observations, was not accurate. More recent observations have shown that a period about 11 seconds shorter than that of System II is better. In fact, the error in the new period is believed to be less than one-tenth of a second.

How is such a precise value arrived at from the radio data? If histograms are plotted year after year, the peaks will always fall at the same longitudes, *provided* the rotation period adopted for the longitude system is correct. If it is not correct, the peaks will "drift" in longitude as the years go by, showing that a revision is needed. Thanks to Shain, the data go back to 1951, so that the

observations now span an interval of 11 years. With a time "baseline" that long, an error of 0.1 sec in the period of the longitude system would give rise to a total drift of 10°, an amount that should be detectable in the histograms.

A number of radio astronomers have now agreed on a longitude system to be called (with no great originality!) System III. The new system rotates with a period of $9^h55^m29^s.37$, and it is defined so that it coincided with System II on January 1, 1957. It is this system that was used in Figs. 4-2 and 4-3.

Optical Features and the Radio Sources. When Shain announced that the Jovian radio signals were coming from a localized source, it was only natural for observers to attempt to associate this source with some visible feature of the planet. Referring to a telescopic sketch of Jupiter made by E. J. Reese on November 30, 1951, Shain himself wrote "Allowing for a continuing drift in longitude, the longitude of the radio source on November 30 would have crossed the middle of one of the prominent white markings in Reese's sketch. Therefore, although the identification is not proved beyond all doubt, it seems very probable that this visually disturbed region was responsible for the radio radiation. . . ." [2]

The reader may be inclined to argue with some impatience that it ought to be a simple matter to decide whether a radio source and a visual marking do or do not coincide. He should remember, however, that the radio data give us only the longitudes of the sources; their latitudes are completely unknown. Even more serious is the fact that the features seen in the telescope are merely the tops of the clouds that shroud Jupiter. As might be expected of cloud formations, individual markings are usually quite ephemeral, lasting a few days, or at most months, and thus discouraging comparison with the radio sources, which by now are known to have been active for over a decade. Surprisingly, however, a few long-lived features have been recorded, and it is these that have attracted the attention of radio astronomers.

The most famous of these persistent markings is the "Great Red Spot," seen in Plate VIII. Drawings made as early as 1831 show the Red Spot, and it is probably identical with a feature

sketched by Hooke in 1664. Thus it goes back at least 131 years, and perhaps as much as three centuries, which is a remarkable lifetime for an atmospheric phenomenon. The physical nature of the Red Spot is as yet unknown. Most students of the planet have regarded it as some kind of body floating in the dense atmosphere; this theory is encouraged by the fact that it frequently fades from sight, as if it had temporarily sunk beneath the clouds. In Fig. 4-5 we see a plot of the longitude of the Red Spot in System II coordinates over a period of ten years. The long-term drift of the Spot indicates that in general it has rotated more slowly than System II. However, the "wiggles" in the curve show that the motion of the Spot has been far from uniform, and at times in the past it has even reversed its drift and rotated faster than System II. It would perhaps be more surprising if the motion of such an atmospheric feature were perfectly regular.

The only other conspicuous, long-lived markings have occurred at nearly the same latitude as the Red Spot. In 1901 a short, dark streak known as the "South Tropical Disturbance" appeared in this region, and for the next four decades it grew in length until it stretched two-thirds of the way around the planet. The Disturbance vanished in 1939, but in that same year a group of three white spots was observed in the belt just south of the Red Spot. These spots, which bear the cryptic designations *FA*, *BC*, and *DE*, have been observed continuously up until the present time. Together with the Red Spot, they constitute the only conspicuous markings now visible on Jupiter's disc that were also present at the time of the earliest radio observations. The spot *FA* may be seen in Plate VIII.

In Fig. 4-5 we have plotted drift curves for the radio sources, the Red Spot, and the white spots. To reduce confusion, only the main radio source (*A*) is shown; the other sources would appear as lines parallel to that of *A*. Similarly, the three white spots are represented by the line for *DE* only. Two things are immediately obvious. First, all these features have quite different rates of rotation, which indicates that there is no physical connection between the radio sources and the optical markings. Second, *because* of the different rates of rotation, temporary coincidences or conjunctions in longitude are not only inevitable,

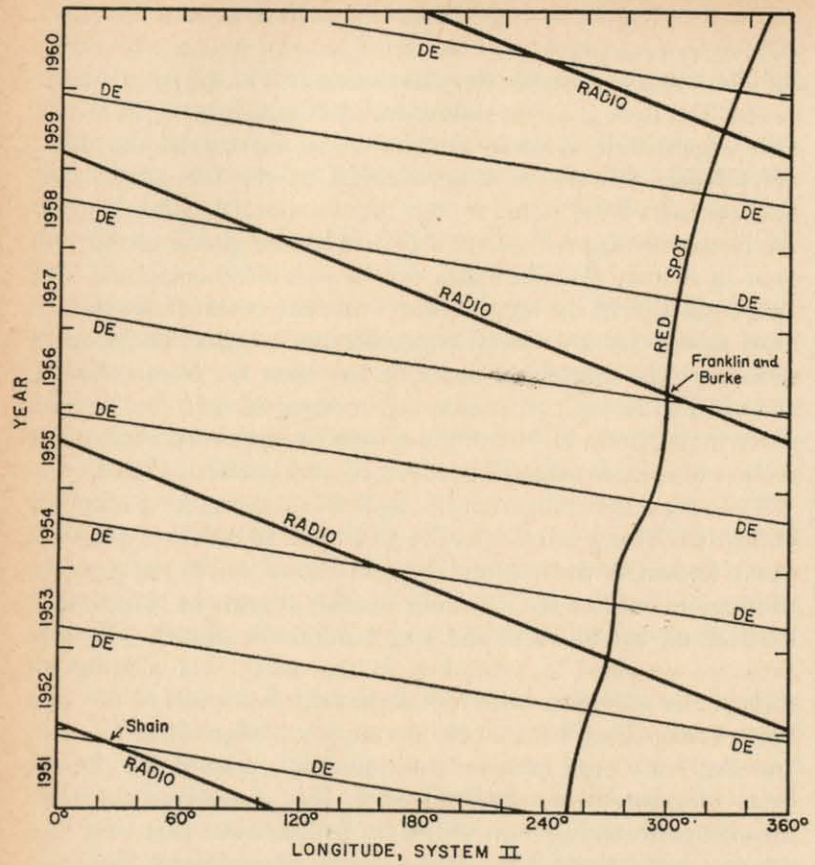


FIG. 4-5 Drift curves of the radio sources and optical markings in System II coordinates. The Red Spot rotates slightly slower than System II, while the radio sources and the white spots (represented by DE) rotate much faster. If a feature rotated at the same speed as the longitude system, its drift curve would be a vertical straight line. (After A. G. Smith and T. D. Carr, *J. Fla. Acad. Sci.* 24, 193 [1961].)

but relatively frequent. The figure shows, for example, that Shain's identification of his radio source with a visual spot was actually due to a temporary conjunction of the main radio source with the white spot *DE*. A conjunction of this same source with the Red Spot in 1956 led Franklin and Burke to speculate briefly

that the famous Spot might be responsible for the radio energy.

Many of the current theories of the decameter sources describe them as phenomena of Jupiter's upper atmosphere, linked to the surface only through the planet's magnetic field. If this is the case, there may well be no associated optical phenomena. One fact seems to be significant in any event. Whether the radio sources are connected with the planet directly or through a magnetic field, there is reason to believe that the radio rotation period of $9^h55^m29^s.37$ is that of the solid surface of the planet—the unseen surface hidden beneath the dense clouds.

DETAILS OF THE DECAMETER WAVES

Frequency Distribution. At what frequency is it easiest to detect the Jupiter signals? Observers have generally found frequencies around 18 to 20 Mc/sec to be the most productive. There is little question that the radiation falls off rapidly at frequencies above 20 Mc/sec. Below 18 Mc/sec the situation is confused by the earth's ionosphere, which, because it is an opaque mirror for low-frequency signals, exerts a two-fold effect. First, the ionosphere may actually reflect incoming waves back into space and prevent them from reaching the antennas. Second, it reflects static from distant thunderstorms, as well as signals from myriads of terrestrial radio stations, into the upward-looking antennas, thus creating a din that drowns out possible radiation from space.

The years that followed the discovery of the Jupiter signals in 1955 were particularly bad in this respect because the maximum of the 11-year sunspot cycle was approaching. Near sunspot maximum the sun is unusually generous in its outpouring of ionizing waves and particles, and as a result the electron density of the ionosphere increases significantly. This increase in the opacity of the ionosphere presented difficulties to those carrying on the work of Franklin and Burke and Shain. Reliable observations could be made only late at night when the ionosphere had grown thinner, and the effective observing season was limited to a few months of the year when Jupiter crossed the meridian between midnight and sunrise.

Early in 1958 the sunspots reached their climax and started to decline. Gradually, low-frequency radio astronomers began to experience relief. It became possible to extend listening periods throughout more hours of the night and through more months of the year. It also became possible to listen at lower and lower frequencies. In 1960 the University of Florida obtained data at 10 Mc/sec, and in 1961 the lower limit of the frequency range was pushed down to 5 Mc/sec.

What have these low-frequency observations revealed? Although the data are still being analyzed, certain broad features of the Jovian radiation are beginning to emerge. If one simply counts the number of occasions on which signals were received, the total increases rapidly toward the lower frequencies. In Fig. 4-6 we have plotted the percentage of nights on which radiation of various frequencies was detected during several months of 1961. (The 5 Mc/sec data are omitted because listening conditions were not yet good enough to make them reliable in this kind of count.) The curve shows that 10 Mc/sec signals were received on nearly every observing night. In fact, during a three-month

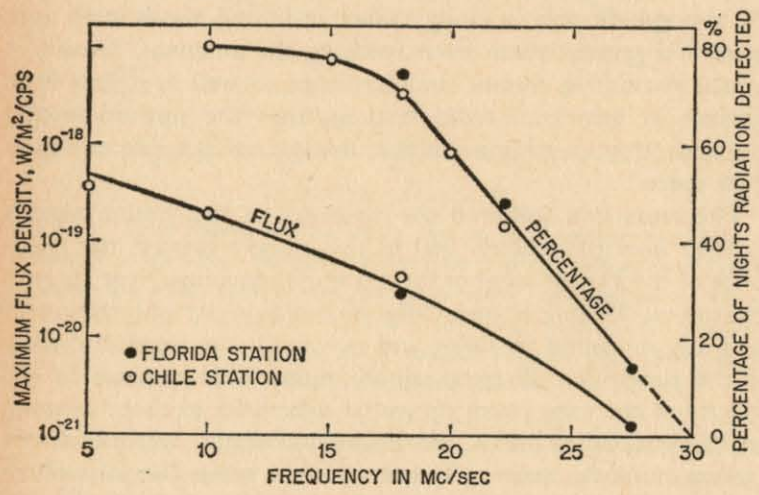


FIG. 4-6 Intensity and frequency of occurrence of Jovian radio outbursts as a function of the observing frequency. (University of Florida data.)

period in which one of the authors made observations from Australia, 10 Mc/sec radiation was detected during 100 percent of the listening periods. On the other hand, 27.6 Mc/sec signals were recorded on only a few percent of the nights.

The *intensity* of the Jovian radiation also seems to rise rapidly as the frequency decreases. Fig. 4-6 shows the average intensity of the five strongest bursts received at each frequency during part of 1961. The increase in energy toward the lower frequencies is so rapid that it is necessary to use a logarithmic scale to represent it adequately. As a matter of fact, about 300 times as much flux is received at 5 Mc/sec as at 27.6 Mc/sec.

Since the Jovian outbursts increase both in number and in intensity at lower frequencies, why have observations near 18 Mc/sec been the most successful? It seems evident that the ionosphere has been the villain. Much of the time, listening conditions have been too poor below 18 Mc/sec to permit effective work. The ideal solution would be to establish a listening post above the troublesome ionosphere—perhaps in a satellite, or better still on the surface of the moon, where large antenna arrays could be erected.

Characteristics of the Bursts. A Jovian outburst may be over in a few seconds, or it may continue for hours. Plate X shows a low-speed recording of a typical "noise storm," as the longer events have been called. Each deflection of the recorder pen during such a storm represents a *burst* of Jovian noise, and high-speed recordings (see Plate XI) reveal that these bursts are generally complex, consisting of a number of individual *pulses*. The elementary pulses commonly range from about 0.2 second to 2 seconds in duration, while the bursts of pulses may last only a few seconds or as much as a minute. On occasion, extremely short pulses having durations of only a few milliseconds have been detected. Heard in a loudspeaker, a strong Jovian noise storm produces an impressive commotion. The sound is best described as a rushing or swishing noise, which has aptly been likened to waves breaking on a beach.

As soon as observers began making simultaneous records at two or more frequencies, it became apparent that there was little correlation between pulses recorded at different frequencies.

A strong pulse might occur at 18 Mc/sec, for example, while a nearby 20 Mc/sec receiver detected nothing. What was the meaning of this? Clearly it indicated that the pulses must have relatively narrow *bandwidths*. In order to study the spectral distribution of energy in the pulses, Dr. N. E. Chatterton of the Florida group assembled a radio spectrograph consisting of a swept-frequency receiver connected to a wide-band rhombic antenna array. This receiver continuously scans any segment of the spectrum up to 4 Mc/sec in width, between 0 and 25 Mc/sec. The signal is displayed on a cathode ray screen, which is photographed by a motion-picture camera. Almost immediately the new equipment showed that the bandwidths of the elementary pulses ranged all the way from tenths of a megacycle to several megacycles. Some of the pulses were quite smooth in form; others were complex, with multiple peaks.

Plate XII shows the build-up and decay of two typical pulses as recorded by the swept-frequency receiver. The first pulse is of the "smooth" variety, while the second displays sharp peaks at several different frequencies. Whatever is causing these bursts must be of a "resonant" nature, since the bandwidths of the pulses range from only 1 percent to about 10 percent of their center frequencies. An electrical circuit having a bandwidth as narrow as this would be regarded as rather sharply tuned.

At Boulder, Colorado, Dr. James Warwick is studying Jupiter with a very wide-band swept-frequency receiver. This instrument scans the radio spectrum all the way from 7.5 Mc/sec to 41 Mc/sec, but in less detail than the Florida receiver. As we see in Plate XIII, Warwick's instrument gives very beautiful displays of the large-scale movement of noise storms up and down the spectrum. In many cases a noise storm appears first at the lower frequencies, and then the center of activity drifts slowly toward the high-frequency end of the scale. On other occasions activity begins at high frequencies, and the drift is toward the lower frequencies. Sometimes the drift is erratic, or there may be no marked drift. It seems to be characteristic of Jovian phenomena that there is no end of variety!

Scintillation. In Chapter 1 we saw that the first discrete source, Cygnus A, was discovered because of its scintillation. It

was also pointed out that such fluctuations are characteristic of sources of small angular extent. Following this line of reasoning, Gardner and Shain wrote, "The angular size of the source on Jupiter is very much smaller than that of any other known radio source, and it would be expected that very severe fluctuations in intensity would sometimes be caused by scintillations in the Earth's ionosphere." [4]

How could one test such a hypothesis? How could fluctuations originating in our ionosphere be separated from "real" fluctuations originating on Jupiter itself? The two Australians reasoned that ionospheric variations should be *local* effects, which would differ from point to point on the earth's surface. Scintillations, whether optical or radio, are much like the dancing patterns of light and shadow seen on the bottom of a shallow, sunlit pool when the water is disturbed. The sun's rays are momentarily concentrated or focused at some points on the bottom, diffused away from others. Gardner and Shain set up two antennas 25 km apart. If they were right, scintillations caused by the ionosphere would reveal themselves by producing different records at the two sites.

On three nights early in 1956 the Australians obtained simultaneous recordings of Jovian signals from their two widely spaced antennas. The records showed marked differences, although every effort was made to keep the two receivers tuned to exactly the same frequency. "It must be concluded," they wrote, "that the terrestrial ionosphere has a considerable effect on the time variations of the Jupiter radiation. . . . The magnitude of the effect, that is, how much of the 'burstiness' of the received radiation is due to the ionosphere, can only be determined by more extensive spaced-receiver observations." [4]

In 1959 the University of Florida set up a radio field station at Maipú, Chile, some 7040 kilometers from the parent observatory. One of the major objectives of the field station was to make simultaneous observations of Jupiter from the ends of this enormous base line. Scores of Jovian noise storms have now been recorded simultaneously at the two stations. While there is excellent agreement regarding the over-all periods of activity, the details of the bursts and of the individual pulses are so distorted as to be unrecognizable when the records are compared.

Is it possible, then, that all the fine structure of the Jovian signals originates in the earth's atmosphere? It does seem certain that much of what Gardner and Shain called the "burstiness" of the radiation—that is, the tendency of the pulses to occur in brief trains or bursts—is the result of scintillation. Often the bursts are received alternately, rather than simultaneously, at the two stations. This alternate fading in and out is well illustrated in Plate XI; it generally occurs with a period of about 30 or 40 seconds, which is highly suggestive, since this is the kind of period that is observed in the scintillation of the discrete sources.

Whether the individual pulses themselves are *formed* by the ionosphere, or merely distorted by it, is not yet clear. During 1961, Douglas and Smith of Yale made simultaneous records over baselines up to 100 km.[5] They found that at times the details of the pulses showed almost perfect correlation, suggesting that the pulses are Jovian after all, or else the ionospheric disturbances responsible for forming them are more than 100 km in extent. This is another problem that could best be resolved by making observations from above the ionosphere!

Polarization of the Signals. In Chapter 2 we discussed the polarization of radio waves and described instruments for measuring this important property. The first measurement of the polarization of the Jupiter signals was made by the Australian team of Gardner and Shain on January 24, 1956. As an indication of the keen competition that often exists in scientific fields, this was the very same date on which Franklin and Burke put a new polarimeter into operation in the United States. Two days later, on January 26, the Americans achieved their first results.[6]

Both teams agreed that the Jovian radiation was circularly or elliptically polarized, and that the sense of rotation of the electric vector was usually right-handed at both observatories. What do these facts indicate? First, they suggest that the signals have passed through an ionized medium immersed in a magnetic field, for such a combination is a likely source of elliptical polarization. Here a familiar problem arises once more: was the polarization created in a Jovian ionosphere and magnetic field, or was

it impressed on the radiation as it passed through the earth's ionosphere and magnetic field?

In response to this question the Australians wrote, "If the sense of rotation is indeed the same when observed in both the northern and southern hemispheres . . . the terrestrial ionosphere cannot be the medium which impresses circular polarization on the Jupiter radiation."[4] What Gardner and Shain meant was that if the earth's field were responsible for the polarization, then the sense of rotation of the electric vector should be reversed for observatories in different magnetic hemispheres of the earth. Since this was not the case, it seemed likely that the polarization was a genuine product of Jupiter itself.

These conclusions were based on only a few observations and, more serious, the northern and southern hemisphere records were not made simultaneously—indeed, could not be made simultaneously because of the difference in longitude between Australia and Washington. An important objective of the Chilean station of the University of Florida Radio Observatory was to add to this scanty polarization data by joining the Florida station in making simultaneous records in both magnetic hemispheres.

What conclusions can now be drawn? The most significant is that the new observations indicate that the sense of rotation is indeed the same in both hemispheres. This sense is generally right-handed, although some instances of left-handed polarization have been recorded. The polarization is usually elliptical, but the eccentricity of the ellipse varies strikingly from burst to burst, and at times the polarization becomes completely circular. Finally, there is some evidence of systematic differences in the polarization of the radiation from the several sources *A*, *B*, and *C*.

The polarization phenomena are rather complex and not easily understood. We have mentioned them here briefly because there is little doubt that they carry an important message concerning the origin of the decameter signals.

ARE THE DECAMETER SIGNALS RELATED TO SOLAR EVENTS?

Solar Stimulation of the Noise Storms. Early in 1958, J. D. Kraus wrote, "It is of interest that the intense Jupiter activity of

February 26, 1957, occurred about four and a half days after a very large solar flare. . . . Also, the intense Jupiter activity of February 14, 1956, occurred about three and a third days after the great eruptive solar prominence which shot off the solar disk at the record velocity of 1100 km on February 10. . . . Although these sequences may be entirely coincidental, they do suggest the possibility that the mechanism producing the Jupiter radiation may be initiated or triggered by particles emitted from the sun." [7]

It is well established that the great solar explosions which astronomers call "flares" shoot out streams of charged particles. A day or two later these particles reach the earth and create such phenomena as the aurora borealis (or "northern lights") and various magnetic disturbances. At such times geophysicists who study the earth's magnetic field speak of "magnetic storms," in referring to the fact that abrupt changes occur in both the magnitude and direction of the field.

In 1959 Eugene Epstein of Harvard suggested to the authors that if Kraus' hypothesis were correct, then when the earth is between Jupiter and the sun the Jovian radio outbursts should be preceded by geomagnetic storms, since the solar particles would strike the earth before reaching Jupiter. During 1961 every effort was made to obtain the best possible data during the critical period when the two planets were properly aligned. When the Jovian observations were compared with the geomagnetic data, there was indeed evidence of a relationship similar to that predicted by Epstein, for on a number of occasions a terrestrial magnetic storm was followed after a delay of about eight days by an outbreak of radio noise from Jupiter.[3]

Is eight days a reasonable time for solar particles to take in traveling from the earth to Jupiter? On eight occasions during the period of the radio observations, solar astronomers actually saw the flare responsible for a given geomagnetic storm. In these cases magnetic disturbances began on the earth from 1.2 to 2.8 days after the flares, and since the distance from the sun to the earth is known, the particle velocities could readily be determined. It was then a simple matter to calculate how much longer the particles would take to reach the orbit of Jupiter if they

continued to travel at the same speed. This additional delay ranged from 5 to 12 days, with an average of 8.3 days. While this does not prove that solar particles trigger the Jovian noise storms, it at least makes it seem more plausible.

Although it is not quite consistent with the phenomena just discussed, there is further evidence of a relationship between solar and Jovian activity. During 1960 Warwick[8] noticed that Jovian noise storms often came after a period in which the decameter emission from the sun had remained at an unusually high level. Solar radiation of this kind, which is called "continuum," is usually associated with activity that leads to the ejection of charged particles. Thus the solar radio noise, like geomagnetic storms, could be used to signal the outward streaming of particles from the sun. While the entire subject of solar relationships is still problematical, it is intriguing to speculate that such diverse phenomena as the aurorae, magnetic storms, and Jovian radio outbursts may all have a common origin!

If the decameter radiation from Jupiter actually is the result of bombardment of the planet by solar particles, might this not produce auroral activity, as it does here on earth? Because we see only the daylight hemisphere of Jupiter, the detection of aurorae poses a difficult problem in optics. Several groups of experimenters have used photoelectric cells in conjunction with astronomical telescopes to record the light from the planet during radio outbursts.[3,9] So far there has been no evidence of light fluctuations associated with the noise storms, but the observations are being continued with more sensitive equipment.

The Long-Term Trend. In the preceding section we have suggested that the radio outbursts on Jupiter may be triggered by solar activity. It would seem to follow, then, that Jovian noise storms should be most frequent near sunspot maximum, when solar activity reaches a peak. Actually, the exact reverse seems to be true!

When the first systematic observations of the Jovian radio signals were made in 1955 and 1956, the sunspot cycle was near its minimum. (See Fig. 4-7.) During the next several years the number of sunspots increased rapidly, whereas there was a marked decline in the radio emission from Jupiter. In 1958 and

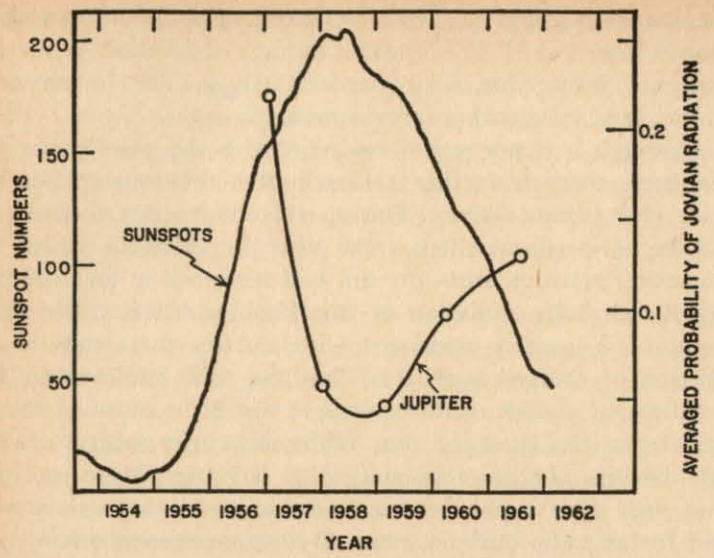


FIG. 4-7 The inverse relationship between sunspots and the average probability of Jovian radio emission. (University of Florida data.)

1959 noise storms were so discouragingly infrequent that one of the authors was led to remark that we seemed to be studying a dying phenomenon. By 1960, however, the sunspot cycle was well past its peak, and Jovian activity began to revive. It occurred to several observers that there seemed to be an *inverse* relationship, or negative correlation, between sunspot number* and Jupiter's decameter emission.

The lower curve in Fig. 4-7 is a plot of what we might term the "average" 18 Mc/sec Jovian emission for each year since 1956. Just how was this curve obtained? First, histograms such as those in Fig. 4-2 represent all of the observations made in a single year, so that the histogram itself is a time average of that year's data. Now, if we add up the lengths of all the vertical

* One might suppose that "sunspot number" would mean the same thing as "the number of sunspots." Actually, the sunspot number R is defined as $k(10g+f)$ where k is a factor (usually near unity) depending on the size of the telescope used in the count, g is the number of *groups* of spots, and f is the number of individual spots. Obviously the effect of the formula is to give high weight to groups.

bars in the histogram and divide by the total number of bars (that is, 72, since we have used a 5° longitude interval), we have in effect also averaged the probability of occurrence over all longitudes. The points in Fig. 4-7 are the yearly, planet-wide averages gotten in this manner. There is no doubt that the trend of the Jupiter data is just the opposite of that of the solar data.

If the reader is somewhat confused at this point, he is in good company. The situation can best be summarized by saying that there is some indication of a short-term, *positive* correlation between individual Jovian noise storms and solar activity, while there is even clearer evidence of a long-term, *negative* correlation between sunspot numbers and the average decameter emission from the planet. Is it possible to reconcile the two points of view? Perhaps solar particles do, in fact, trigger the noise storms, but near sunspot maximum the Jovian ionosphere, like that of the earth, becomes more opaque and the radiation simply fails to escape into space. Or, as Warwick has suggested, perhaps interplanetary space itself becomes so contaminated with solar particles that it partially blocks the Jovian signals.

THE ANOMALOUS MICROWAVE RADIATION

History of the Observations. In Chapter 3 we recounted the early history of the microwave observations of Jupiter. The reader may recall that between 1956 and 1958 several groups of radio astronomers made measurements at wavelengths near 3 cm. While the results were not of great accuracy, they seemed compatible with the accepted temperature of the planet. It was only when McClain and Sloanaker repeated the experiment at a wavelength of 10 cm that students of Jupiter received a shock. The measurements yielded an average temperature of 580° K, or more than four times the earlier value. Clearly, something was wrong!

Intrigued by this unexpected result, a number of observers who had the necessary large "dishes" and sensitive receivers hastened to train them on Jupiter. By the end of 1959 the planet's temperature had been measured at wavelengths of 21, 22, 31, and 68 cm. The results are shown in Table 4-1.

TABLE 4-1 *Microwave Observations of Jupiter**

Wavelength (cm)	Received Flux ($w/m^2/cps$) $\times 10^{-25}$	Brightness Temperature (°K)	Observers
3.2	1.5	140	Mayer, McCullough, Sloanaker
10.3	0.63	580	McClain and Sloanaker
21.	0.60	2500	McClain
21.	0.71	3000	Epstein
22.	0.65	3000	Drake and Hvatum
31.	0.60	5500	Roberts and Stanley
68.	1.1	50,000	Drake and Hvatum

* Data for this table were selected from a more extensive table compiled by C. H. Mayer in *Planets and Satellites*, edited by G. P. Kuiper and B. M. Middlehurst (University of Chicago Press, Chicago, 1961).

The striking thing about the observations was that over a wavelength range of more than 20 to 1 there was little change in the received flux density. What did this imply? Since Eq. 3-2 shows that the radio flux from a true blackbody radiator should fall off as the inverse square of the wavelength, it will be evident why radio astronomers were convinced that Jupiter's nearly flat microwave spectrum could not result from simple thermal radiation.

The third column of Table 4-1 shows the calculated "temperatures" that result if one still insists on interpreting the received flux as thermal radiation emanating from the whole disc of Jupiter. It would be difficult to argue that the temperatures implied by the longer-wavelength data are realistic! As in the case of the decameter waves, it appears that some complex, nonthermal mechanism is at work generating radio energy of unexpected intensity.

Changes in the Microwave Energy. Perhaps the most outstanding feature of the decameter radiation from Jupiter is its variation with time. The decameter signal ranges from essentially zero to a strength rivaled only by the sun, and as we have seen, the changes are closely coupled with the rotation of the planet. On the other hand, there has been doubt as to whether the microwave radiation changes at all, and even greater uncertainty as

to the association of the suspected fluctuations with Jupiter's rotation or other phenomena.

It is a difficult task merely to *detect* the microwave radiation from a planet, let alone to measure small changes. As Fig. 3-6 shows, even the relatively strong signal from Venus is nearly obscured by noise fluctuations. In Fig. 4-8 are plotted the Jovian

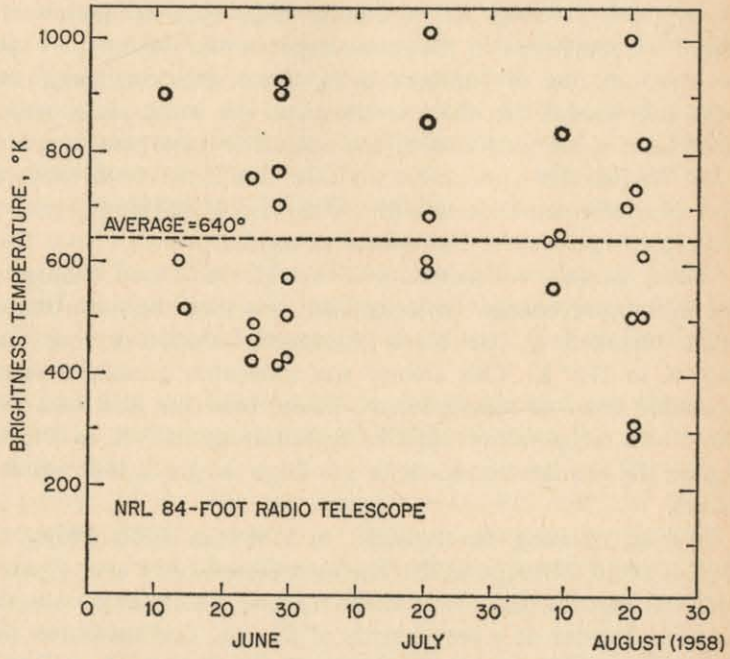


FIG. 4-8 Fluctuations in the measured 10-cm brightness temperature of Jupiter (After R. M. Sloanaker and J. W. Boland, *Astrophys. J.* 133, 655 [1961].)

temperatures computed by the Naval Research Laboratory from two months of observations in 1958. It is evident that there are large fluctuations even in the results of a single day. How much of this variation might be real and how much instrumental is difficult to say. The reader can, at least, appreciate the problem facing the microwave observer.

The group at the Naval Research Laboratory suspected that

their 10-cm and 21-cm data showed higher temperatures for one hemisphere of Jupiter than for the other. However, since the difference was no greater than the random fluctuations in the data, no real conclusion could be drawn. Other workers reported that there was no significant correlation of the radiation with Jupiter's rotation at wavelengths of 3, 22, 31, and 68 cm. The most intriguing report came from a group at Columbia University who recorded an unusually high 3-cm temperature at about the same time in 1958 that a spectacular outbreak of spots occurred in one of Jupiter's belts. Since these markings were near the central meridian at the time the radio measurement was made, a connection with the optical features was suggested. Alas! No further associations of this kind have been reported, and the microwave correlation with visual markings seems to have gone the way of its decameter counterpart.

There is more substantial evidence for *long-term* changes in the microwave energy. Between 1957 and 1958 the 3-cm temperature recorded at the Naval Research Laboratory rose from 145° K to 173° K. This change was somewhat greater than the probable error of measurement. Then, between 1958 and 1959 the 10-cm temperature apparently fell from 640° K to 315° K. Again, the change seemed to be too large to attribute to random errors.

A most exciting development occurred in 1961. Using the 60-foot radio telescope of the Harvard Observatory over a period of seven months, Dr. M. S. Roberts made a total of 90 observations of Jupiter at a wavelength of 21 cm. The measured flux varied some 250 percent, while the fluctuations in two discrete sources used for comparison were much less. Most significant of all, the increases in the Jovian flux seemed to occur from 2 to 6 days after increases in solar activity. Historically, it is interesting to note that in 1959 McClain of the Naval Research Laboratory had commented on an apparent rise in Jupiter's 21-cm temperature following a great solar flare and intense auroral activity on the earth. Once more we have an intriguing interplay between the decameter regime and the microwave regime, with the sun perhaps playing the role of matchmaker.

A Jovian Radiation Belt. Public interest is always aroused by any resemblance of another planet to the earth. In 1959 Dr. F. D. Drake of the National Radio Astronomy Observatory caught the attention of the press by suggesting that Jupiter's microwave energy might arise in radiation belts surrounding the planet in the manner of the now-famous Van Allen belts of the earth. At the time this was no more than an ingenious speculation based on the fact that particles trapped in a radiation belt could, at least in principle, emit radiation of the kind observed. Within less than a year Drake's theory was confirmed.

During April of 1960, Radhakrishnan, Roberts, and Morris of the California Institute of Technology used two 90-foot paraboloids as a giant interferometer to study Jupiter at a wavelength of 31 cm.[10] The big "dishes" were mounted on railroad tracks, and the distance between them could be increased up to 1600 feet. With this base line the disc of Jupiter could be partially resolved—enough to show that the microwave flux was coming from a halo surrounding the planet, just as Drake had predicted.

By rotating the waveguide horns that received the energy at the foci of their antennas, the Californians were also able to determine the polarization of the waves. It turned out that about 30 percent of the flux was linearly polarized, with the electric field lying roughly parallel to Jupiter's equator. As the planet rotated, however, the plane of polarization seemed to oscillate through an angle of roughly 18°, which suggested that the halo was wobbling.[11]

In Fig. 4-9 we see the picture of the Jovian Van Allen belt that has evolved as the California and Harvard scientists continue their studies. The radiation appears to be concentrated in a thin ring with a diameter about three times that of the planet itself. Within this region the flux is partially plane polarized, with the electric vector parallel to the plane of the ring. The oscillation of the plane of polarization can be explained most simply by assuming that the ring is tipped about 9° with respect to Jupiter's axis of rotation, so that it wobbles as the planet turns.

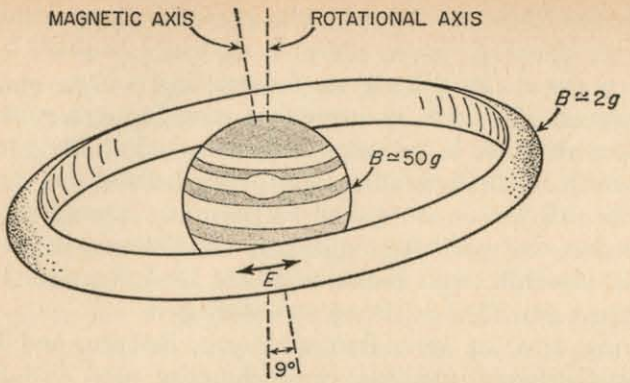


FIG. 4-9 A concept of the Jovian radiation belt that is responsible for the nonthermal microwave emission.

What does all of this mean? We shall see in the next chapter that it is quite consistent with a picture in which Jupiter is surrounded by a vast radiation belt tied to the planet by a tilted magnetic field much like that of the earth.

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5 *The Origins of Planetary Radio Signals*

In Chapter 4 we saw that the planet Jupiter emits a radio spectrum of astonishing intensity and complexity. What is the cause of this seemingly unique behavior? We can begin our speculation with the knowledge that Jupiter is by far the largest of the sun's family of planets. Could such emission be characteristic only of planets so massive that they have just escaped being self-luminous like the stars?

ENERGIES OF THE JOVIAN OUTBURSTS

Because Jupiter and the sun are the only celestial bodies definitely known to emit sporadic radio outbursts, it is natural to compare their radiation. We found in Chapter 4 that the strongest Jovian bursts had been observed at a frequency of 5 Mc/sec, where the received flux density approached 10^{-18} w/m²/cps. It happens that this same figure represents an upper limit to the intensity of ordinary solar bursts in the decameter wavelength range,* and thus we see that the two bodies produce about the same maximum signal at our antennas. But wait! Even at its

* On March 8, 1947, a solar burst was recorded which rose above 10^{-15} w/m²/cps at 60 Mc/sec. Perhaps this is a "world record." Nevertheless, bursts in excess of 10^{-18} w/m²/cps are unusual events and could not be regarded as representative.

closest approach Jupiter is four times as far away as the sun. Since flux density falls off as the inverse square of the distance, the signals from the planet must actually be 16 times as strong as those from the sun! When we remember that the area of the sun is 100 times that of Jupiter, and that temperatures in the solar atmosphere exceed a million degrees, this is indeed a surprising conclusion.

Let us estimate the energy contained in a Jovian pulse. It is easy to see that if the planet radiated uniformly in all directions, the total power P that it emits would be equal to the flux density S at the earth, multiplied by the area of a sphere whose radius is equal to the distance D from Jupiter to the earth. (See Fig. 4-4.) If we take $D = 5.9 \times 10^{11}$ m at Jupiter's closest approach, then $P = 10^{-18}$ w/m^2/cps $\times\ 4\pi(5.9 \times 10^{11})^2$ m$^2 = 4.4 \times 10^6$ w/cps. However, a Jovian source does *not* radiate in all directions, but only in a limited cone, so that the power we have just derived is too large. Let us take the half-angle α of the cone to be 30°, which Figs. 4-2 and 4-3 show to be a reasonable average. The area a intercepted by the cone in Fig. 4-4 is then about 1/15 of the total area of the sphere, and P is reduced to 3×10^5 w/cps.

Now we are in a position to estimate the energy content of a pulse. Since spectral studies (see Plate XII) show that a typical pulse has a bandwidth of about 1 Mc/sec, the total *power* radiated is $P_T = 3 \times 10^5$ w/cps $\times\ 10^6$ cps $= 3 \times 10^{11}$ w, or 3×10^8 kw. Finally, taking one second as the average duration of a pulse, the *energy* contained in the outburst is 3×10^{11} joules.

What do these numbers mean in terms of more familiar quantities? An electrical generating capacity of 3×10^8 kw would exceed that of all of the power plants in the United States. We might also compare the energy of a pulse with the explosion of a ton of TNT, a unit that, for better or worse, is familiar to every newspaper reader. Since such an explosion releases 4×10^9 joules, the radio energy in our Jovian pulse is equivalent to 75 tons of TNT. If the reader is disappointed at the modest size of this figure, he can take comfort in R. M. Gallet's observation that in other natural phenomena, such as lightning strokes or solar shock waves, only one part in 10^5 of the total energy is converted into radio waves.[1] Thus, the Jovian event responsible for our pulse

may involve as much as 10^{16} joules of energy, placing it well in the "megaton" range of the TNT scale.

If one were stubborn enough to insist that the decameter radiation is simple thermal energy despite the fact that its spectrum is all wrong, what temperature would be required to produce the observed 5 Mc/sec flux? Even if we assume that the radiation comes from the entire surface of Jupiter, Eq. 3-5 tells us that the temperature would have to reach the fantastic value of 3×10^{15} °K. Worse yet, we have seen that the radio signals come from limited areas of the planet rather than from the whole disc, so that these regions would have to be even hotter than 3×10^{15} °K. Since the hottest stars have surface temperatures of only 10^5 °K, it is easy to see why no one believes that Jupiter's decameter energy is simple heat radiation. Even in the microwave region Eq. 3-5 predicts the unrealistically high temperatures shown in Table 4-1. Only when we get to wavelengths of less than 10 cm does the radiation appear to be largely thermal.

JOVIAN THUNDERBOLTS

There has never been any lack of speculation about the origin of Jupiter's radio noise. Shortly after Burke and Franklin discovered the decameter outbursts in 1955, the editors of the scientific journal *Nature* wrote, "The radio emissions were reported to have the appearance of short random bursts of static resembling thunderstorm interference on a broadcast receiver. . . . It has been suggested that the Jupiter signals are caused by disturbances in the planetary atmosphere similar to terrestrial thunderstorms, but on a much larger scale."[2]

How do the Jovian bursts compare with our own lightning strokes? Could a terrestrial thunderstorm be detected if it were transported to Jupiter? A lightning discharge radiates roughly 4×10^5 w/cps at a frequency of 5 Mc/sec. If we assume that this energy is emitted equally in all directions, the flux density at the distance of Jupiter would be 10^{-29} w/m^2/cps. Not only is this signal far too feeble to be detected by present instruments, it is 10^{11} times weaker than the strongest 5 Mc/sec bursts that are actually observed from the giant planet. If they are to explain

the radio signals, the Jovian thunderbolts must indeed be "on a much larger scale"!

Although the thunderstorm theory was a simple and natural explanation of the decameter radiation, it was criticized as early as 1955 by the British radio astronomer F. G. Smith. As an alternative, Smith suggested that energy for the radio outbursts might be supplied by the differential rotation of the planet's atmosphere —that is, by the slippage of the various cloud belts with respect to each other and with respect to the surface of Jupiter.[3] Smith failed to explain how this rotational energy was to be converted into radio signals, but in 1960 G. B. Field of Princeton pointed out that a *dynamo* mechanism might supply the answer.[4] The differential rotation of the planet and its atmosphere means that Jupiter's magnetic field must be cutting through the gases of the atmosphere just as the magnetic flux in a dynamo cuts through the windings of the machine. Field reasoned that under proper conditions—probably in the thin upper atmosphere of the planet —this action might induce electric fields strong enough to create spark discharges. Although this hypothesis resembles the thunderstorm theory, it is sufficiently different to remove some of the objections. Recent theories, however, seem to have dismissed the electrical discharge as a possible source of the Jovian radio signals.

PLASMA OSCILLATIONS

A few years ago the word "plasma" was familiar only to a small group of specialists who studied electrical discharges in gases. Almost overnight "plasma physics" became an important new field of science, owing its rapid growth to the key role played by plasmas in attempts to tame the hydrogen bomb and generate useful power from nuclear fusion reactions. What is a plasma? Actually, it is nothing more than an ionized gas that has acquired a new and glamorous name. Anyone who is reading this book by the light of a fluorescent lamp has a plasma at his service, for the glowing mercury vapor in the lamp is largely plasma.

Normally, electrons and positive ions are intermingled uniformly throughout a plasma, so that any small volume is electrically neutral. However, the electrons are far more mobile than

their heavier partners, and a disturbance may produce a momentary separation of unlike charges. As soon as the disturbing force is removed, the electrical attraction between positive and negative charges attempts to restore equilibrium, but the particles "overshoot" their original positions and an oscillatory motion results.

In 1958 the Russian theorist V. V. Zhelezniakov suggested that Jupiter's decameter radiation might be due to plasma oscillations in the ionosphere of the planet.[5] According to Zhelezniakov, the turbulent churning evident in the Jovian atmosphere "can cause rapid displacements of the ionospheric plasma in the magnetic field of the planet"; these displacements then induce localized electric fields. Up to this point the Russian's theory resembles Field's dynamo mechanism, but Zhelezniakov used the induced field merely as the initial disturbance needed to start plasma oscillations. Now, a plasma oscillation is a *longitudinal* wave, and normally it cannot excite electromagnetic radiation, for the latter is a transverse wave.* However, Zhelezniakov argued that the electron density in the Jovian ionosphere is probably quite nonuniform, and under such conditions conversion of plasma oscillations into radio waves does become a possibility. The theory seemed even more reasonable because several kinds of solar radio bursts were already attributed to plasma oscillations.

Nor was Zhelezniakov the only advocate of this theory. Gallet and the Australians F. F. Gardner and C. A. Shain[6] contributed the intriguing suggestion that Jupiter's ionosphere might be set into oscillation by shock waves ascending from volcanic explosions on the surface of the planet. The notion of Jovian volcanoes is one that stems from earlier years when the planet was thought to be incandescent, and it has persisted throughout a period in which our concept of Jupiter changed from that of a seething inferno into a world of ice.

PARTICLES FROM THE SUN

We saw in Chapter 4 that there is reason to suspect that Jupiter's radio emission may be associated with the sun. In both

* In a longitudinal wave the oscillatory motion is back and forth, parallel to the direction of travel of the wave. In a transverse wave the oscillation is at right angles to the direction of travel.

the microwave and the decameter regions, increases in Jovian activity have been observed after solar outbursts. If this relationship proves to be valid, what can be the nature of the mechanism linking the two bodies?

The most likely answer lies in the great streams of charged particles—mostly electrons and protons—that the sun spews into space during the spectacular solar explosions that we call "flares." We have seen that these particles create a variety of disturbances as they flow past the earth, and it is believed that the capture of some of this solar material by the earth's magnetic field is responsible for the formation and maintenance of the Van Allen radiation belts which surround our planet. If we may assume that the particle streams ultimately reach Jupiter, it is likely that similar events take place there, with many of the particles being "trapped" in the Jovian magnetic field. The actual observation of a microwave halo surrounding the giant planet has removed all doubt as to the soundness of this picture, and most of the recent theories of Jupiter's radio spectrum have been based on the emission of signals by electrons imprisoned in a Jovian radiation belt.

The Decameter Radiation. As early as 1958 T. D. Carr[7] suggested that the elliptical polarization of the decameter radio waves could be explained if the signals were *cyclotron radiation* from solar electrons spiraling along lines of Jupiter's magnetic field. Every student of physics knows that charged particles moving at right angles to a magnetic field are forced into circular orbits. This guided motion is in fact the basis of operation of accelerators such as the cyclotron and the betatron. If the particles also have a component of velocity *along* the magnetic field, their paths become helices centered on the lines of the field.

Electrons in orbits such as those we have been discussing make 2.8 B million revolutions per second around the magnetic field lines, where B is the intensity of the field in gauss. As a consequence, the electrons emit radio waves of the same frequency,

$$f_c = 2.8\,B \text{ Mc/sec.} \qquad (5\text{-}1)$$

It is customary to refer to f_c as the "cyclotron frequency," and the emitted waves are called "cyclotron radiation." An observer

would find such radiation to be elliptically polarized unless he happened to be situated directly along the lines of the field or at right angles to them.

Fig. 5-1 shows the trajectory of an ion that has been trapped

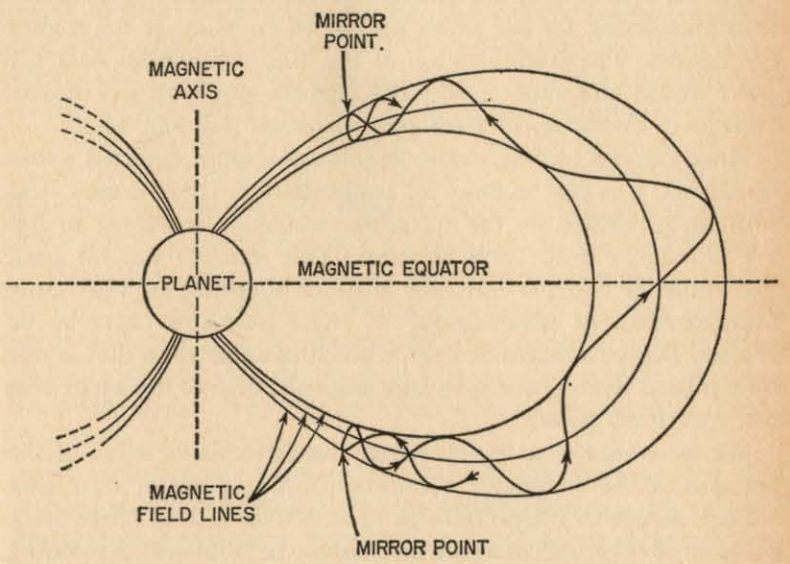


FIG. 5-1 Trajectory of an ion trapped in the magnetic field of a planet.

in the magnetic field of a planet. Following the lines of the field, the particle spirals toward one of the magnetic poles. As the field increases near the pole, the helical path of the ion is compressed more and more, until the particle is finally "reflected" and sent back in the opposite direction. In this manner an ion can oscillate indefinitely from pole to pole unless some disturbance "dumps" it out of its stable orbit. A *radiation belt* is formed by a large assemblage of such particles oscillating in similar trajectories. The details of why belts are formed in certain regions—or how particles become trapped in the first place—are not well understood even for the earth.

According to the cyclotron picture of Jupiter's decameter radiation, radio bursts at different frequencies are emitted by particles spiraling in different regions of the magnetic field. Eq. (5-1) sug-

gests that low frequencies are radiated by electrons moving in the weak field above the planet's equator, while the higher frequencies come from the polar regions, where the field is strongest. Because ions are repelled by regions of increasing field (see Fig. 5-1) fewer electrons would actually reach the vicinity of the poles, thus accounting for the rapid decline in emission at the higher frequencies. The concentration of the high frequencies near the poles would also explain why the angular extent of the sources appears to shrink as the frequency increases. (See Fig. 4-2.)

Since Fig. 4-6 indicates that signals are seldom detected above 30 Mc/sec, it is easy to place an upper limit on the magnetic field ordinarily reached by the spiraling electrons. According to Eq. 5-1, $B = f_e/2.8 = 30/2.8 \cong 11$ gauss. This result is not far from the value of 7 gauss that the authors obtained in 1958 from measurements of polarization.[8] If these estimates prove to be correct, Jupiter's magnetic field is much stronger than that of our own planet. Even at the magnetic poles the field of the earth does not exceed 0.7 gauss.

We have seen that the cyclotron theory explains many of the features of the decameter radiation. Does this mean, then, that we can accept this hypothesis as proven? Not at all. There are a number of other speculations that cannot be dismissed. According to Warwick, the signals may be due to *Čerenkov radiation,* a type of emission that occurs only when charged particles travel through a medium so fast that they outrun their own electromagnetic waves.[9] Another possibility is that the impinging solar particle streams may produce plasma oscillations or waves of several other kinds in the Jovian ionosphere, any one of which could give rise indirectly to radio signals. For example, a stream of electrons can transfer its own energy to weak electromagnetic waves that it encounters, thereby intensifying the waves to the point where strong emission occurs. Termed "traveling-wave amplification," this mechanism is believed by Gallet and R. A. Helliwell to be responsible for certain low-frequency radio signals that have been observed on the earth.[10] The reader can see that there is no shortage of hypotheses to account for Jupiter's decameter radiation! The real problem is to choose correctly from among the many possibilities.

The Microwave Radiation. We have seen that cyclotron radiation might account for Jupiter's long-wavelength outbursts. Could it also explain the microwave emission? Nonthermal energy is observed at frequencies at least as high as 3000 Mc/sec, and Eq. 5-1 tells us that it would take a magnetic field of 1100 gauss to whirl electrons at this frequency. Such a field is perhaps not impossible, but it is so large as to seem unlikely. Fortunately there is a way out of the difficulty. If the spiraling electrons have energies high enough to place them in the "relativistic" range—meaning that they are traveling so fast that their masses have increased appreciably, as predicted by the theory of relativity—they will radiate not only the fundamental cyclotron frequency, but numerous harmonics of this frequency as well. Such emission is called *synchrotron radiation,* after the nuclear accelerator in which it was first observed. Radio astronomers are now intensely interested in the synchrotron process because it is believed to account for such important phenomena as the cosmic radio noise from the galaxy, the emission of the discrete sources, and certain types of solar outbursts.

The synchrotron principle greatly reduces the magnetic field needed to account for Jupiter's microwave spectrum, for now the fundamental cyclotron frequency can be nearly as low as one pleases. Furthermore, if the electrons are energetic enough, the harmonics become so numerous as to merge together in a broad, continuous spectrum of just the kind that is actually observed. Detailed theories have been worked out by a number of scientists, including Field of Princeton[11] and J. A. Roberts and G. J. Stanley of the California Institute of Technology,[12] and it now appears that much of the microwave energy can be attributed to synchrotron emission from fast electrons trapped in the Jovian equivalent of our own Van Allen belts. Even the observed polarization effects can be accounted for, since the synchrotron process produces linearly polarized radiation.

What of the wobbling of the radiation belt and the consequent oscillation of the plane of polarization? This is easily explained if Jupiter's magnetic field is tipped about 9° with respect to the axis of rotation, for of course the orientation of a radiation belt follows that of the magnetic field. Indeed our own Van Allen

belts must perform the same kind of gyration in space, since the earth's magnetic axis is tilted 11° from the axis of rotation.

As we have indicated in Fig. 4-9, synchrotron theory suggests that the magnetic field in Jupiter's radiation belt is about 2 gauss, which would lead to a surface field of 50 gauss at the planet's equator—a value 150 times as large as that of the equatorial field of the earth. These values are quite compatible with the estimates on p. 104, if the decameter signals arise along field lines somewhere between the equator and the poles. The principal problem that remains is to account for the large flux of relativistic electrons that must be present to cause the observed microwave emission. M. S. Roberts and G. R. Huguenin of Harvard have speculated that electrons may be accelerated to the required velocities by so-called "hydromagnetic waves," or undulations of Jupiter's outer atmosphere, produced when solar plasma streams collide with the planet.[13]

The giant planet does not give up its secrets easily, however. During 1962 Roberts and Huguenin discovered that it is only the *polarized* component of Jupiter's nonthermal emission that fluctuates in response to solar activity (p. 94), implying that the other component has a different origin. It now appears that the microwave energy is a mixture of no less than three separate ingredients —ordinary thermal radiation from the surface of the planet corresponding to a temperature of about 140° K, synchrotron emission from solar electrons in the radiation belt, and a third component of unknown origin. If this last constituent were thermal radiation from a different layer, as some have suggested, it would imply a temperature in excess of 2000° K. It could also come from the random motion of electrons in Jupiter's ionosphere, but the latter would have to be 100 times as dense and 5 times as thick as the ionosphere of the earth. Since neither of these conditions seems likely, we are left with another mystery.

If Jupiter is surrounded by a radiation belt that is a source of intense radio emission, one cannot help wondering why we are not overwhelmed by powerful signals from our own radiation belts. Surely they are far closer than the radiation belt of Jupiter! The answer probably lies in the high density of the earth's ionosphere relative to the intensity of the surrounding magnetic field. At the distance of the outer Van Allen belt the earth's field has fallen to a mere 0.01 gauss, and the cyclotron frequency of electrons in this region is only about 30 kc/sec. Near the inner belt the field is ten times stronger, but the cyclotron frequency is still only 300 kc/sec. Frequencies as low as these cannot penetrate the ionosphere (unless by some freak mode of propagation), and thus we are effectively screened from cyclotron radiation in the Van Allen belts. But what of synchrotron radiation? It would take enormous numbers of highly relativistic electrons to generate strong synchrotron emission at frequencies that could get through the ionosphere, and apparently such a particle flux is not present. An observer in space might find that the earth emits a radio spectrum similar to that of Jupiter, but at far lower frequencies.

IS JUPITER UNIQUE?

We have now devoted two chapters to a single planet. Why? The reason, of course, is that Jupiter is the star radio performer among the bodies that circle the sun. In Chapter 3 we found that Venus has a microwave spectrum of unusual interest, but the strong decameter outbursts that were once reported have never been confirmed. Observations of Mars and Uranus have also failed to disclose any nonthermal signals within reach of present equipment.

On a number of occasions observers at Yale[14] and at the University of Florida[15] have detected possible decameter bursts from Saturn. In every case the radiation has been so weak and so fleeting as to defy positive identification. It is evident that the signals, if they exist at all, are far less frequent and much less intense than those from Jupiter. Should we really expect radio outbursts from Saturn? On the one hand Saturn more nearly resembles Jupiter in size and appearance than does any other body in the solar system, and so by analogy we might expect the ringed planet also to emit decameter radiation. On the other hand, the rings of Saturn may well interfere with the formation of a radiation belt and thereby prevent the emission of nonthermal radio waves.

Planetary radio astronomers are continuing to keep a wary eye on Saturn in hopes of discovering which of these arguments is more valid.

In the spring of 1957, scientists at the Ohio State University and at the Royal Observatory of Belgium reported radio signals from the conspicuous comet Arend-Roland.[16] (See Plate XIV.) The American observations were made at 27.6 Mc/sec, where the maximum flux was 5×10^{-22} w/m^2/cps, while the Belgians measured a flux of 8×10^{-23} w/m^2/cps at 600 Mc/sec. Other radio astronomers failed to detect any emission from Arend-Roland, and there have been no further reports of radio signals from comets although several comets have subsequently been observed rather carefully. Like the decameter radiation from Saturn, the radio observation of comets must for the present be placed in the file marked "uncertain."

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6 *Radar Astronomy*

Man has yearned for knowledge of the heavens since the dawn of reason. He began the systematic study of astronomy thousands of years ago. But confined as he was to an isolated island in the infinite celestial laboratory, he was unable to perform controlled experiments with the objects he was studying. He could only observe. The application of radar to astronomy was therefore an outstanding achievement, for it enabled man to experiment at last with the moon, the sun, and the nearer planets. The even more incredible fact that he will shortly visit some of these bodies should not detract from the distinction held by radar as the first means whereby astronomers could actively probe the solar system.

THE EARLY HISTORY OF RADAR ASTRONOMY

The history of radar astronomy began in 1926 when Breit and Tuve demonstrated the radar principle by obtaining echoes of transmitted radio pulses, which they correctly attributed to reflection from the ionosphere. In 1928, Heising observed brief

echoes indicating transient increases in the electron density of the lower ionosphere. Skellett's suggestion that these increases might be due to ionization by meteors was verified by Schafer, Goodall, and Skellett in 1931, when they found that the bursts of ionization often appeared simultaneously with visible meteors. The first report of the reflection of continuous-wave signals by meteors was made in 1941 in India by Chamanlal and Venkataraman, who heard weak whistles of rapidly varying pitch when they tuned to the unmodulated carrier of the Delhi radio transmitter 10 miles away. The whistles were the beat frequency between the direct wave from the transmitter and the wave reflected from ionization near the moving meteor head, with the latter shifted in frequency because of the Doppler effect.

The systematic development of radar astronomy as a research field, however, did not occur until after the invention of military radar during World War II. By the end of the war radar techniques had been perfected, and with the cessation of hostilities radar equipment became available for research purposes.

Modern radar astronomy had its beginning in 1946 when echoes were obtained from the moon by J. H. De Witt and E. K. Stodola[1] of the U. S. Army Signal Corps and radar was applied to the study of meteors by Hey and Stewart[2] in England. In their successful attempts to obtain lunar echoes, De Witt and Stodola employed modified 115 Mc/sec military radar apparatus. A 3000-watt pulse of 0.3-second duration was transmitted every 4 seconds, and a weak echo from the moon was received as expected about 2.5 seconds after the transmission of each pulse. The intensities of successive echoes varied, and at times the signal faded completely.

Almost simultaneously with the achievement of De Witt and Stodola, Z. Bay[3] in Hungary also obtained radio echoes from the moon. Although his measurements were of questionable value, other than proving that echoes could be obtained, the fact that he was able to succeed at all with the limited facilities at his disposal was noteworthy. The recording apparatus employed by Bay was most unconventional. It consisted of a battery of water voltameters successively connected to the receiver output after the transmission of each pulse. The presence or absence of echoes was

deduced from the quantity of hydrogen gas liberated in the various cells after the apparatus had been in operation for a while—an example of the use of integration techniques to detect a weak periodic signal in the presence of strong background noise.

In 1947 moon echoes were obtained in Australia at the relatively low frequencies of 18 and 22 Mc/sec by Kerr, Shain, and Higgins,[4] who used short-wave broadcasting stations for transmitting the pulses. Kerr and Shain proved that the observed fading of the signals was of two types, with the period of one type being a few seconds and that of the other several minutes. The short-period fading was shown by Kerr and Shain to be due to *libration*, which is the apparent rocking motion of the moon as seen by an observer on earth. Since the echo signal is a composite of the contributions from various scattering centers on the moon's surface, the phase relationships between these signal components change as the moon rotates relative to the earth, giving rise to the short-period fading.

The correct explanation of the slow fading was not forthcoming until 1954, when W. A. S. Murray and J. K. Hargreaves[5] showed that it was produced by *Faraday rotation*—that is, by the rotation of the plane of polarization of the outgoing and returning waves as they traverse the earth's ionosphere. Since the magnitude of the Faraday rotation varies with ionospheric conditions, the plane of polarization of the received signal changes, so that it is sometimes parallel to the polarization of the antenna and sometimes perpendicular. In the former event the echo is received with maximum strength, while in the latter case no signal at all is detected.

The use of radar to study meteors also developed rapidly after the war. The pre-war radio contacts with meteors had added little to the knowledge acquired from optical observations. The systematic application of radar to the investigation of meteors was initiated by Hey and Stewart in 1946, and it revolutionized meteor science. Since that time the rate at which information has been acquired by radar has greatly exceeded that obtained by optical means.

Hey and Stewart used military radar operating at 70 Mc/sec to study meteor echoes occurring at altitudes of about 100 km.

Since this frequency is far above the critical frequency of the ionosphere, complications of purely ionospheric origin experienced in the earlier investigations at lower frequencies were avoided. Hey and Stewart proved conclusively that echoes occur when the ionized meteor trail is perpendicular to the direction of propagation from the radar apparatus (as Pierce had suggested in 1938). They also showed that most, if not all, visible meteors passing perpendicularly through the antenna beam gave rise to echoes, and that there were many invisible smaller meteors that produced echoes. In all cases of reflection from meteor trails, the range remained approximately constant while successive echoes diminished in intensity. This effect was attributed to dispersal of the column of ionization left by the passing meteor. Hey and Stewart occasionally observed a faint, fast-moving echo preceding the stationary main echo, which they interpreted as a reflection from the moving head of the growing ionization column. These relatively rare events provided direct measurements of the velocities of the meteors responsible for the ionization.

Following the early moon-echo experiments and the pioneer meteor investigations of Hey and Stewart, centers of research in radar astronomy appeared in various parts of the world, particularly in England, the United States, and Canada. Refined lunar echo experiments have yielded much new information, the distance to Venus has been measured by radar with considerably greater accuracy than hitherto possible by optical means, and echoes have been obtained from the sun, Mars and Mercury. In the discussion that follows, no attempt will be made to present these later developments either chronologically or completely. Only the barest essentials of radar astronomy and very brief accounts of the more interesting results can be given here.

METEOR ASTRONOMY

The Nature of Meteors. Cruising along in its orbit about the sun, the earth crosses the paths of myriads of small but swift fragments of iron and stone. Most of these *meteoroids* are mere specks of dust. A few are as heavy as a gram, and once in a while a really large chunk appears. On entering the earth's atmosphere,

the dust specks are slowed down rapidly. Having relatively large surface-to-mass ratios, they manage to radiate away frictional heat fast enough to avoid being incinerated. Their cosmic velocities lost, they lazily settle through the atmosphere until some days later they reach the level where weather is formed; here they act as nuclei about which water droplets condense, and finally they ride the raindrops to earth.

The fate of the occasional large meteoroid is more spectacular. Rushing in flames behind a cap of air compressed to incandescence and trailing a wake of shock waves, it may be seen by multitudes, and headlines will tell of the "fireball." If it was large enough to begin with, part of the meteoroid may even survive to strike the earth.

However, our concern is with the fragments of intermediate size that never reach the ground—those that weigh less than a gram, but are larger than dust particles. As it shoots into the atmosphere, such a fragment collides with individual atoms or molecules of air. The atoms stick to the fragment, and the kinetic energy imparted by each collision raises the temperature of the meteroid ever higher. Soon its surface melts and begins to vaporize. The tremendous speed of the fragment itself becomes the main velocity component of the evaporated atoms, and it gives rise to kinetic energies approaching 1000 electron volts. The collisions of these relatively high-energy atoms from the fragment with other air molecules produce heat, light, and ionization. If the original meteoroid weighed more than a milligram or so, it will be visible to the naked eye as a *meteor*; if smaller, it will be invisible, and only by the radar reflections from its trail can its presence be known.[6]

About three quarters of the total number are "sporadic" meteors, which arrive from random directions and may occur at any time. "Shower" meteors account for the other quarter. All the meteors in a given shower come from the same direction in space and have very nearly the same velocities. The rate of occurrence of meteors during a shower is usually many times that of the sporadic meteors. Although all the meteors in a given shower arrive from the same direction in space, the effect of perspective is to make their paths appear to radiate outward like the spokes

of a wheel from a fixed point among the stars called the "radiant." Showers may last from a few hours to a few days, and they usually recur at intervals of one year.

A shower is caused by the passage of the earth through a well-defined stream of particles that orbit the sun with almost identical velocities. It is believed that such a stream consists of debris left behind by a comet. In most cases the debris is rather uniformly distributed about the orbits, and it is not associated with active comets. Such debris is probably the residue of comets that have long ago disintegrated. When the earth crosses the orbit of an *active* comet, the resulting meteor shower is usually greater the closer behind the comet the crossing occurs, which would seem to indicate that the debris trailing behind young comets has not yet had time to disperse about the entire orbit.

Before the advent of radar, meteor astronomy depended entirely upon optical observations, visual and photographic. Only the larger meteors, occurring during good weather on moonless nights, can be detected optically. A photographic method, which utilizes a pair of widely spaced cameras for measuring meteor trajectories and velocities, was perfected by Whipple.[7] Although the method is capable of the highest precision, the number of meteors that come into the field of view of both cameras and are bright enough to be photographed is discouragingly small. In about 15 years of operation, only five double-station photographs yielding good velocity and position measurements were obtained. Another limitation of the optical method is its inability to detect meteor showers in the daytime. The radar method, on the other hand, is not affected by daylight, moonlight, or clouds, can detect meteors smaller than the visible limit, can provide velocity and position data for a relatively large percentage of the detectable meteors, and can also yield a great deal of information on upper atmospheric conditions.

The Investigation of Meteors by Radar. A typical radar system used for meteor research may consist of a transmitter that is repetitively pulsed, a receiver, an antenna that is switched back and forth between transmitter and receiver, a pair of cathode ray tubes for displaying range and echo amplitude as functions of time, and a photographic method of recording the range vs. time

and amplitude vs. time curves. The brief pulse of electromagnetic radiation that leaves the antenna at the start of each measurement interval travels at the rate of 3×10^8 m/sec toward the meteor. Upon striking the ionized trail of the meteor, a small fraction of the radiation is scattered back toward the antenna. This feeble echo is received and amplified and then converted into voltages that will deflect or intensify the cathode ray spots.

The *range oscilloscope* provides a continuous indication of echo time, which is proportional to the distance to the meteor trail. The cathode ray spot is swept linearly in the vertical direction in synchronism with the pulsing, and the intensity of the spot is controlled by the receiver output. When no echo is being received, the spot is too faint to be seen, but it is brought to full brilliancy by the echo signal. Thus the height at which a bright spot recurs along the vertical sweep is a measure of the range to the meteor trail. The spot is photographed with a film moving horizontally at uniform speed, and the successive images of the spot trace out a curve of range as a function of time. (See Fig. 6-1.)

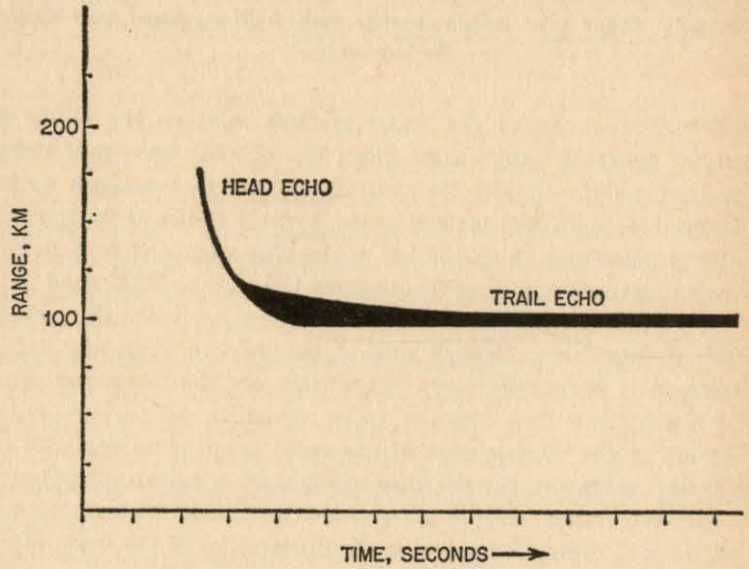


FIG. 6-1 Radar range-time record of a meteor for which echoes were obtained from the approaching head and afterward from the trail.

The other oscilloscope is connected to the receiver in such a way that the spot (which in this case is of constant brilliancy) deflects upward a distance that is proportional to the amplitude of the echo signal. This spot too is photographed with a horizontally moving film, so that successive echoes give rise to a series of spikes of varying height. The envelope of the tops of the spikes is a plot of echo amplitude as a function of time. (See Fig. 6-2.)

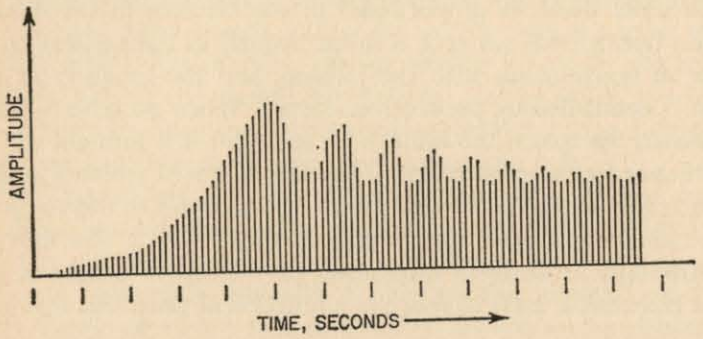


FIG. 6-2 Radar echo amplitude-time record of a meteor trail during its formation.

The frequencies of the radar systems used in the study of meteors generally range from about 30 to 80 Mc/sec—well above the ionospheric critical frequency, and yet low enough to be scattered from ionized meteor trails. Typical values of transmitter power range from 10 to 100 kw, with pulse widths from 3 to 100 μsec and pulse repetition frequencies from 30 to 2000 cps.[8]

In the case of most meteors, echoes first appear when the meteor trail reaches such a length that a straight line from the radar intersects it perpendicularly. From then on, the range indicator shows a more or less constant value, which is the perpendicular distance to the meteor trail. If the radar beam is narrow and its direction is known, the position of the point of nearest approach of the meteor trail can be ascertained. Additional information is necessary in order to determine the orientation of the trail. However, in the case of shower meteors, the right ascension and declination of the radiant can be deduced from a series of observations made in different directions with a single narrow-beam radar.

For a few of the brighter meteors, a faint echo from the moving head of the growing ionization column can be seen preceding the stronger trail echo, as in Fig. 6-1. Thus the changing range of the meteor itself can sometimes be recorded from the time of acquisition to the time of closest approach, and the approximate velocity of the meteor can then be determined. A broad antenna pattern is desirable for such measurements in order to obtain maximum coverage, but this precludes the measurement of direction, and consequently the path cannot be fixed in space. On the other hand, if the moving "head echo" can be recorded simultaneously by three radar sets at known locations (preferably at the corners of an equilateral triangle), then both the position in space and the velocity of the meteor can be determined as functions of time.

Since the occurrence of head echoes is rather rare, meteor velocity measurements are more often made by another method, which utilizes the *diffraction* of the radio waves scattered from the trail. The phenomenon that is involved is known in optics as "knife-edge diffraction," and it is explained in most general physics texts. Diffraction by a meteor trail is illustrated in Fig. 6-3. Waves from the radar transmitter, located at point O, strike the ionized meteor trail and are scattered back down. To simplify the explanation, let us assume that the meteor trail is a very thin, straight column. Each segment of the column can be considered as point source contributing to the radiation scattered back to the antenna. The relative phases and amplitudes of the radiation components arriving at the antenna from the various point sources depend on the total distances they have traversed. The resultant signal amplitude is the vector sum of all the component amplitudes, and it can be computed by vector integration. The Cornu spiral, familiar to students of optics, is a nomogram from which the resultant amplitude and phase can be measured directly.

In Fig. 6-3, the meteor trail grows toward the left as the meteor advances. The graph at the top of the figure shows how the resultant amplitude of the signal received at the antenna varies

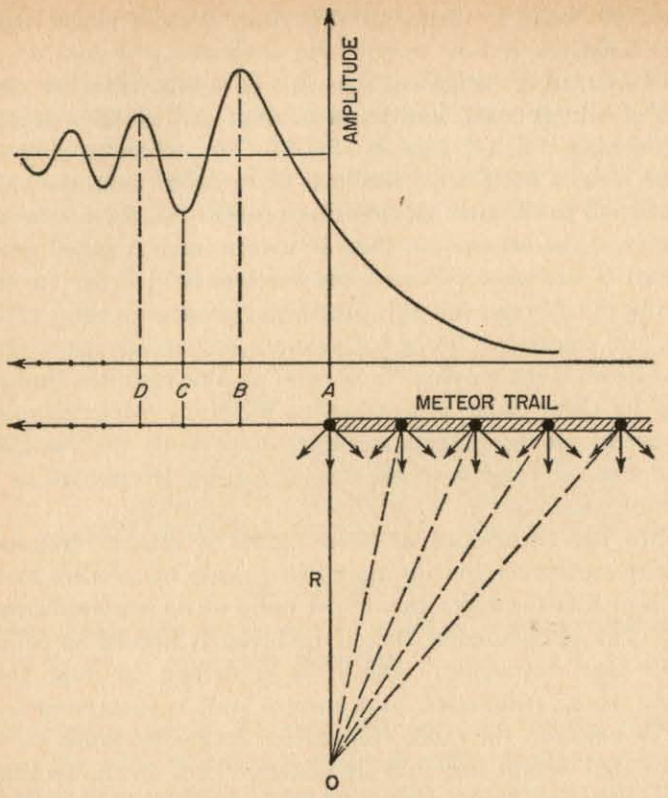


FIG. 6-3 Radar diffraction by a meteor trail. The meteor is moving from right to left and the radar is at O. The graph shows relative amplitudes of echoes as the trail extends toward the left.

with the extension of the trail. The amplitude increases until the head of the column reaches point *B*. However, between *B* and *C* the amplitude decreases since the wave components from the new point sources which are added *beyond B* are more or less out of phase with the resultant of all the sources *behind B*. As the column head progresses farther, the resultant amplitude oscillates as shown because the round-trip distances *OAO*, *OBO*, *OCO*, *ODO*, etc., are successively longer by a half wavelength, so

that those sources in segments *AB* and *CD* increase the resultant amplitude, while those in *BC* tend to cancel it.

It can further be shown that the velocity of the head of the ionized column, and hence that of the meteor itself, is given by the formula

$$V = \frac{0.3\sqrt{\lambda R}}{t},$$

where t is the time between the occurrence of the first maximum and the first minimum in the diffraction pattern (at *B* and *C*, respectively, in Fig. 6-3), R is the perpendicular distance to the meteor trail, as indicated by the radar range oscilloscope, and λ is the wavelength. Thus the velocities of most of the meteors detected by radar can be determined from the echo amplitude vs. time record (Fig. 6-2) and the indicated trail range.

Some Results of Radar Meteor Studies. There are about 15 major meteor showers, each of which has its own date of reappearance. Because three of these showers always occur during daylight hours, they were unknown until the advent of radar astronomy, and they still can be observed only by this technique. The meteor velocities, which range from 20 to 60 km/sec, have to a large extent been determined by radar measurements.

All the shower meteoroids are moving in elliptical orbits about the sun, although some of the orbits are so extended that they approach parabolic shapes in the vicinity of the earth. Before the introduction of radar, it was suspected that sporadic meteors were in some cases arriving from outside the solar system, in which event their orbits would be hyperbolic instead of elliptical. With the aid of elementary dynamics it can be shown that a meteoroid in a parabolic orbit about the sun would have a velocity with respect to the sun of 42.2 km/sec at the distance of the earth's orbit. Meteoroids crossing the earth's orbit with velocities greater than 42.2 km/sec must be traveling along hyperbolic paths, while those moving slower than this must be in elliptical orbits.

The average speed of the earth itself in its nearly circular orbit about the sun is 29.8 km/sec. If there were no hyperbolic meteoroid paths, then the highest observed velocities of meteors in the earth's atmosphere should result from head-on collisions of the

earth with meteoroids traveling at the limiting parabolic velocity. The maximum measured velocity should then be less than 42.2 + 29.8 + 1.0 = 73 km/sec, the additional 1.0 km/sec resulting from the attraction of the meteoroid by the earth. On the other hand, if an appreciable fraction of the meteors were in hyperbolic orbits, measured velocities greater than 73 km/sec would be common. That such is not the case was proved independently by McKinley in Canada and by Almond, Davies, and Lovell in England, who showed from radar studies of meteor velocities that all meteoroids describe elliptical orbits about the sun, and that none are visitors from interstellar space.

As a matter of fact, Davies, using the three-station radar measurement technique described earlier, subsequently demonstrated that most sporadic meteors have a relatively short orbital period of about two years. The orbits of many of the sporadic meteoroids are similar to those of asteroids, the tiny planets that congregate largely in the space between the orbits of Mars and Jupiter. This fact would seem to indicate that sporadic meteors are merely very small asteroids, and that there may be a more or less continuous gradation in the sizes of such objects, from the largest asteroid (probably about 500 miles across) to particles of meteoric dust.

Radar estimates of the masses of meteoroids can be made from the observed amplitudes of the echoes, together with the ranges. Masses can also be estimated from the brightness of visible meteors. Determinations have been made of the average mass distribution of the sporadic meteors from 0.001 mg to 100 mg. The incidence rate for the entire earth increases monotonically from 10^6 meteors per day with masses between 100 mg and 10 mg, to 6.5×10^{10} per day with masses between 0.01 mg and 0.001 mg. About 50 kg of sporadic meteors in each mass decade enters the atmosphere every day. Excluding the *meteorites* (that is, those meteors that reach the ground), the total mass of sporadic meteors entering the atmosphere is probably close to 750 kg per day. The total mass of meteorites reaching the earth's surface is about 550 kg per day. An average mass of 250 kg per day is brought into the atmosphere by shower meteors. Differences in the mass distributions of the meteors in different showers are probably related to differences in age.[9]

The study of meteors by means of radar has added much to our knowledge of the upper atmosphere. The heights at which meteor trails are observed range from about 60 km to 120 km. Atmospheric pressures and ionic recombination rates in this region can be determined from the echo measurements, and wind velocities can be determined from the drifts of the meteor trails.

RADAR AS A LUNAR AND PLANETARY PROBE

Requirements and Techniques. Detection sensitivity requirements for meteor radar are no more stringent than those for conventional antiaircraft radar. However, because of the tremendous distances involved, the detection of echoes from the moon or other bodies of the solar system presents a far greater problem.

To appreciate the magnitude of this problem, let us determine how the echo power decreases with the distance D to the reflecting target. Suppose that the radar transmitter emits pulses of P_T watts. If G is the gain of the antenna (which is used for both transmitting and receiving) and D is the distance to the target, the power per unit area at the target will be $GP_T/(4\pi D^2)$. The fraction of the incident radiation that is returned toward the radar will depend upon the size, shape, orientation, and material of the target. The reflecting ability of the target can be specified by σ, the cross-sectional area of a perfectly isotropic scatterer that would return the same power toward the radar as does the actual target. The received echo power is the same as though the power $\sigma GP_T/(4\pi D^2)$ had been reradiated equally in all directions from the target. Thus the echo power per unit area at the antenna is $\sigma GP_T/(4\pi D^2)^2$ and the total received power is

$$P_D = \frac{P_T G \sigma A}{(4\pi D^2)^2} = \frac{P_T \sigma A^2}{4\pi \lambda^2 D^4} \qquad (6\text{-}1)$$

where A is the effective area of the antenna and $G = 4\pi A/\lambda^2$. Eq. 6-1 is known as the Radar Equation. It is evident that for a given radar system, the received echo power varies as σ/D^4.

A conventional long-range antiaircraft radar system can just detect an aircraft of 100-foot wing span at a distance of about 200 km. The value of σ for such an aircraft has been found to be about 40 m². For a rough spherical body like the moon, it was estimated that σ should be of the order of 0.1 of the cross-sectional area of the body. It follows that σ/D^4 for the moon is about 1/1000 that for the aircraft, and thus a thousand-fold increase in sensitivity is necessary for lunar observations. Even this sensitivity does not approach that required for detection of the other members of the solar system, as can be seen from Table 6-1.

TABLE 6-1 *Detectability of Various Radar Targets Relative to the Moon*

Target	Estimated value of σ/D^4 (relative to value for moon)
Large aircraft at 200 km	1000
Moon	1
Sun	$<1 \times 10^{-5}$
Venus	2×10^{-7}
Mars	1.3×10^{-8}
Mercury	1.7×10^{-9}
Jupiter	3.3×10^{-10}
Saturn	1.7×10^{-11}
Uranus	1.7×10^{-13}
Neptune	2.3×10^{-14}

The more extended the target, the longer are the pulse lengths that must be employed to attain the echoing areas upon which the values of σ/D^4 in Table 6-1 are based. Pulse lengths of a microsecond or so are sufficient for aircraft detection, and the shorter the pulse, the better the range accuracy. For spherical targets of astronomical size, however, it would seem that the pulse durations should be at least as great as the time required for a radio wave to travel twice the radius of the body so that radiation reaching the radar antenna from the nearest part of the visible hemisphere will still be arriving when that from the more remote points first arrives. By this criterion, the lengths of lunar radar pulses should be greater than 11.6 milliseconds. However, Evans[10] and Trexler[11] have shown that most of the lunar echo is returned from a relatively small central region of the

visible hemisphere, which can be adequately covered by pulses of half a millisecond duration. Longer pulses, presumably proportional to the radii, must be used to attain the full echoing areas for bodies larger than the moon.

Eq. 6-1 shows that the range D of a radar operating at a given wavelength can be increased by increasing the transmitted power P_T, by increasing the antenna area A, or by reducing the minimum detectable signal P_D. The first two factors are limited by the prohibitive cost of achieving great increases in transmitter power or antenna area, but large increases in receiver sensitivity are feasible.

The minimum detectable radar signal power is determined by the background noise level, which is proportional to the receiver bandwidth. Only about 1/1000 as much bandwidth is required if pulse durations of the order of milliseconds rather than microseconds are used. Since the background noise will be reduced in the same ratio as the bandwidth, the use of the longer pulses results in a thousand-fold increase in sensitivity. This increase is sufficient to permit the detection of lunar echoes without requiring excessive transmitter power or antenna area.

The additional tremendous increase in sensitivity necessary to obtain radar echoes from Venus has been attained largely through the use of long-time integration techniques for detecting periodic signals that are far below the background noise level. The unique method devised by Bay in his pioneer lunar radar investigations is an example of such a technique. The Venus radar integration systems are, of course, far more refined. In the method used at the Millstone Radar Observatory (Massachusetts Institute of Technology),[12] a train of uniformly spaced pulses was transmitted for a time slightly less than the expected round trip echo delay, which varied between 283 and 449 seconds during the experiments. Just before the arrival of the first echo pulse, the transmitter was shut down and the antenna was connected to the receiver. Since the motion of Venus relative to the earth causes a Doppler shift in the echo signal frequency, the receiver had to be adjusted to this estimated frequency.

The receiver output was fed in digital form to a computer at regular intervals which were a small fraction of the pulse recur-

rence period, T. Let us assume that the first receiver reading was made at an integral number times T seconds after the beginning of the first transmitted pulse, and was averaged with all subsequent readings occurring at intervals of exactly T. Similarly, the second reading was averaged with all those which followed *it* by integral multiples of T seconds, and so on. The averages were then displayed as a function of the time between the start of each reading period and the selection of the sample to be averaged.

During the portions of the reading periods containing no echoes, the observed averages were due to the noise level alone. However, those averages taken over the portions containing echoes were slightly higher. It was necessary to average over thousands of reading periods before the increase caused by the echoes was discernible. A single five-minute observation by this method yielded only the fraction of a period by which the echo time exceeded an integral multiple of T, but the multiple itself was undetermined. However, it was possible to eliminate this ambiguity by making repeated observations with different pulse recurrence periods, all the while keeping track of *changes* in target range (which could be determined unambiguously).

Radar Studies of the Moon. The use of radar provides much information about the surface of the moon. Recently developed techniques permit the determination of the relative amounts of echo radiation scattered from various regions of the lunar surface. A statistical analysis of such results gives some indication of the distribution of surface irregularities. Calculation of the average dielectric constant of the scattering material is also possible, since the radar reflectivity of a material depends on its electrical characteristics as well as on its smoothness.

Although the radar antenna beams used to date are not narrow enough to determine directly the variations in echo brightness across the lunar surface, scanning can be accomplished by other means, including range scanning. It is now possible to obtain echoes of relatively short transmitted pulses (30 μsec or less) from the entire visible hemisphere. The echo pulses are greatly elongated in comparison with those transmitted because of the variation in range of different parts of the curved surface. The power at a given instant within each echo pulse is a measure of the

back-scattering by a narrow, circular strip of lunar surface at the range corresponding to that echo time. As time passes, this circular strip, which is centered on the point nearest the earth, expands and progresses outward to the rim of the lunar disc.

The relative power in an average lunar echo pulse as a function of time beyond the leading edge is shown in Fig. 6-4 for each of two frequencies, as reported by Evans.[13] The transmitted pulse lengths were 30 μsec. The drop-off beyond the leading edge is very sharp, with most of the energy in the first 300 μsec. This decay becomes less after a millisecond or two, and the pulse ends at about 11 milliseconds. The general shape of these curves is accounted for by assuming that the reflected radiation contains both a specular and a diffuse component. The specular component accounts for the sharp peak at the leading edge. It results from mirror-like reflections by a number of areas near the center of the moon's disc that are relatively flat (compared to a wavelength) and are almost perpendicular to the incident rays. The diffuse component results from scattering by surface irregularities of sizes comparable to a wavelength, which are distributed over the entire hemisphere. Thus the scattered component in Fig. 6-4 is greater relative to the specular component at 3.6 cm than at 68 cm wavelength. The distribution of scattering centers over the lunar surface can be inferred from the variation of echo power with range at various wavelengths.

A second scanning technique makes use of the Doppler effect. As seen from the earth the moon slowly rocks from side to side, as well as up and down, through small angles. Because of this "libration," as it is called, various points on the lunar surface move toward or away from the earth at different velocities and the echo spectrum is broadened by the resulting Doppler shifts. The scattering contribution from all surface points that produce a given Doppler shift can be deduced from the power spectrum of the echoes. Maps of the radar scattering by the lunar surface have been prepared by Pettengill[12] from the data obtained by combined range and frequency scanning. Since a contour of equal range on the lunar surface intersects a contour of equal Doppler shift at *two* points, such maps are ambiguous. The rotational velocity of libration can also be determined by simultaneous meas-

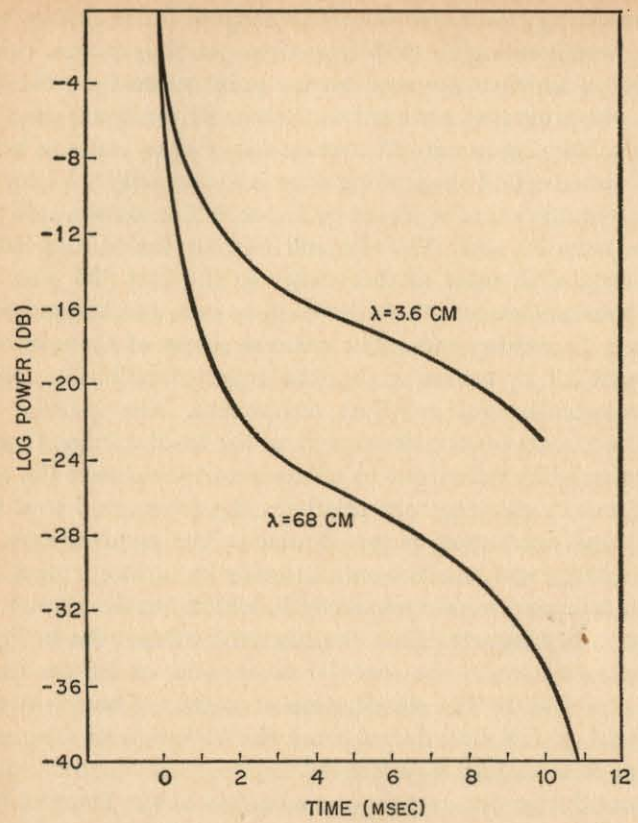


FIG. 6-4 Relative power as a function of time for lunar echo pulses. Time is measured from the leading edge. The transmitted pulse length was 30 μsec at both wavelengths. (After J. V. Evans, *Radar Astronomy*, unpublished course notes, MIT, 1962.)

urements of Doppler broadening and echo intensity as a function of range.

From an analysis of the data presented in Fig. 6-4, Evans has concluded that most of the lunar surface is smooth and undulating, with average gradients of about 1 in 10 for points separated by 68 cm, and of about 1 in 7 for points separated by 3.6 cm. Only 8 percent of the surface is covered with structures whose size approximates a wavelength of 68 cm, while 14 percent of the

surface contains irregularities comparable to a wavelength of 3.6 cm. Using a value for the radar cross section of the moon obtained by Fricker, *et al.*, Evans has calculated the average dielectric constant of the lunar surface material as 2.8. This value, he points out, is approximately the same as for dry sand, and only half the value for solid rock. He concludes that the lunar surface must be porous, with a density about 40 percent that of solid rock.[13]

The Astronomical Unit. Angular measurements made with the optical telescope long ago provided highly accurate knowledge regarding the shape of the earth's orbit. Through observations of the direction of the sun relative to the stars at various times throughout a given year, the corresponding directions of the earth from the sun could be obtained. At the same times, the *relative* distances of the earth from the sun were determined from the apparent solar diameter, which decreases, of course, as the distance increases. *Absolute* distances could not be measured by this method, since the true diameter of the sun was not known.

The orbits of most of the planets relative to that of the earth were ascertained with high precision many years ago by triangulation from different points on the earth's orbit at two times when the planet was at the same point in its own orbit. Planetary orbits can be computed by a more modern method from a few accurate measurements of angular position and the application of the theory of gravitation, but the scale of absolute distance is again undetermined. These methods give accuracies of a few parts per million for the relative positions of the sun, the earth, and the other planets at any time.

If the absolute distance between any pair of these bodies can be measured, then the absolute positions of all the planets relative to the sun can be determined as a function of time. One method of establishing such an absolute distance involves the measurement of the *aberration of light,* the slight displacement of the image of a star caused by the lateral velocity of the telescope as the earth circles the sun. From this measurement we can determine the orbital velocity of the earth, which in turn enables us to compute the average distance from the earth to the sun. This distance, which we call the "astronomical unit," establishes

the scale for all the planetary orbits. The values of the astronomical unit as determined by optical means range from 149,419,000 (±120,000) km[14] to 149,674,000 (±17,000) km.[15] These values differ by almost two parts in 10^3, and since all astronomical distances (stellar as well as planetary) are based on the astronomical unit, it was important to find a method by which this relatively large uncertainty could be reduced. Since radar range measurements can be made with very high accuracy, the determination of any interplanetary distance by radar would thus be expected to result in a substantial reduction in the uncertainty.

The first successful radar contact with another planet occurred in 1961 when three American groups (Millstone Radar Observatory Staff,[16] Victor and Stevens,[17] and Maron, *et al.*[18]), a British group (Thomson, *et al.*[19]), and a Russian group (Kotel'nikov[20]) succeeded almost simultaneously in determining the distance to Venus. The method employed by the Millstone Observatory group has been described earlier. Each of the five groups calculated the value of the astronomical unit on the basis of its measured distance to Venus. The Millstone result was 149,597,850 (±400) km. The values obtained by the others were close to this, the maximum difference between any pair of the five values being about three parts in 10^5. The uncertainty in the value of the astronomical unit as measured by radar is undoubtedly much less than for optical determinations—apparently by one or two orders of magnitude. Further refinement of the radar value is expected.

Radar's Contribution to the Mystery of Venus. As we learned in Chapter 3, because the surface of Venus is perpetually obscured by clouds the rotational period is unknown, and it has been impossible to learn anything of the nature of the surface during the centuries that the planet has been under telescopic scrutiny. Radar, on the other hand, readily penetrates the clouds, and the observed echoes are due to reflection at, or just beneath, the surface. As in the case of the moon, much can be deduced from the echoes concerning the rotation of the planet and the structure and electrical characteristics of its surface.

Most of the energy in a Venus radar echo is near the leading edge of the pulse—as was true of the moon—indicating that most of the reflection occurs from the nearest part of the planet. Studies

by Evans[13] of the echo pulse shape lead to the conclusion that the Venusian surface is smoother than that of the moon, at least in terms of irregularities greater than a radar wavelength. From his experimentally determined value of the radar cross section, Evans has deduced that the average value of the dielectric constant of Venus' surface material is about 4.1. This is about the same as the value for quartz, and it is consistent with the idea that the Venusian surface is largely rock.

Attempts to determine the rotational period of Venus from the Doppler broadening of the echo spectrum have been made by Kotel'nikov and by Evans.[13] The results were not conclusive. Kotel'nikov gave a value of 10 days, while Evans' measurements indicated that the period lies between 115 days and 500 days. Optical measurements by Dollfus[21] in 1955 suggested that Venus rotates in such a way that it always maintains the same face toward the sun, in which case its rotational period would be 225 days. Evans' radar measurement is not inconsistent with this possibility.

THE FUTURE OF RADAR ASTRONOMY

Radar echoes have now been obtained from the moon, the sun, Venus, Mars, and Mercury. Jupiter will probably be detected by equipment now in the planning stage,[13] but radar detection of the planets beyond Jupiter (or perhaps Saturn) in the near future is improbable. Radar contact with even the nearest star is entirely out of the question with present methods. Although refinements in technique will steadily increase the amount and the quality of information to be gained by radar from the moon and the nearer planets, the value of such information will naturally be lessened as space science develops. The future of *solar* radar astronomy, however, appears more promising, since space probes are not apt to offer much competition in this area.

Radar echoes from the sun were first obtained by Eshelman, *et al.*, in 1959.[22] The sun is a poorer radar target than Venus because the noise it generates interferes with the reception of echoes, and heavy absorption of the signals occurs as they pass through the solar corona. Nevertheless, radar measurements made

by the MIT Lincoln Laboratory[23] indicate that useful information can be obtained from the sun. Eventually, radar will probably be used to obtain ion density distributions in the corona and to determine the structures and velocities of the ionized clouds ejected from the sun.

In June of 1962, when Mercury was near its minimum distance of 52 million miles, a team of Soviet scientists led by Kotel'nikov succeeded in establishing radar contact with the little planet.[24] It is believed that the Russian antenna system was a group of eight 53-foot parabolic dishes designed for communicating with space probes, and that the transmitter power was somewhat in excess of 100 kilowatts. At the operating frequency of 700 Mc/sec the reflection coefficient of the planet was about 0.06, similar to that of the moon, although the echo signal was too weak to permit accurate measurements to be made.

The first radar contact with Mars was achieved late in January of 1963 by W. K. Victor and R. Stevens of the California Institute of Technology's Jet Propulsion Laboratory.[24] An 85-foot parabolic antenna was used to transmit 100-kilowatt signals at a frequency of 2388 Mc/sec. After a round trip of 11.1 minutes when Mars was at its minimum distance of 62 million miles, about 10^{-21} watt of this power was received back at the antenna as an echo. The initial results indicate that the radar reflectivity of Mars is between that of Venus and the moon, and that the roughness of the reflecting portion of the Martian surface varies as the planet turns on its axis.

Much remains to be learned from the further study of meteors by radar. It may become possible to detect some of the larger asteroids with earth-based radar, and asteroids of all sizes with a rocket-borne radar system transported into the asteroid belt. Radar echoes from ionized gases in the heads of comets are a distinct possibility and would provide much-needed information on the nature of these mysterious space travelers. It is also possible that radar beacons will be planted by rocket on planets and asteroids to permit more accurate determinations of interplanetary distances.

It is inevitable that the importance of the exploration of the planetary system by radar will diminish as instruments and men

are carried directly to the scene by space vehicles. However, that time is still to come. In the meantime, the information that radar provides will be vital in man's great effort to conquer space.

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7 *Radio Astronomy and the Space Age*

Radio astronomy has much in common with the exploration of space. Each field received its principal impetus from the technological advances of World War II. Each is a new and exciting science which promises to add greatly to man's understanding of the universe in which he lives. We have called attention to instances in which the two fields are engaged in friendly competition, yet it happens more often that they tend to support each other. On the one hand, space research offers the radio astronomer an opportunity to lift his instruments beyond the restrictions of their present environment—even to carry them to other bodies of the solar system. On the other hand, the techniques developed by radio astronomers have, not surprisingly, turned out to be closely related to those needed in tracking and communicating with space vehicles.

THE ROLE OF RADIO ASTRONOMY IN SPACE

Both radio astronomy and space research are, at their roots, fundamental sciences. That is, each is a search for knowledge in which the principal driving force is man's curiosity rather than thoughts of an immediate "practical" return. Yet history teaches us that there are few discoveries of science that are not sooner or later drawn into the service of mankind, and the interval between the discovery and its utilization seems to shorten with each generation. Emphasizing this point, the noted British radio astronomer Sir Bernard Lovell wrote of his great 250-foot radio telescope, "It is not part of my daily job to seek any possible practical outcome of my work; and the large sums of money which have been given for radio telescopes in this country were invested in faith for the free investigation of the universe. But the first use of the telescope which was conceived and built to study the universe was the detection and tracking by radar of the launching rocket of the Russian Sputnik." [1]

What are some of the contributions of radio astronomy to space science? There is little doubt that the demands of radio astronomy stimulated the development of large antenna systems and ultrasensitive receivers just prior to the time such facilities were needed in the space effort. So similar are the requirements of radio astronomy and space research that much of the time of Sir Bernard's radio telescope has been devoted to tracking satellites and space probes, rather than to making astronomical observations. Other major installations, such as the Millstone radar in Massachusetts and the Goldstone radar in California, divide their time in a similar way.

In Chapter 1 we found that Jansky's discovery of cosmic radio noise went unheeded by radio engineers because they felt that the signals were too weak to be of practical importance. Today the situation is quite different. Receivers based on masers or parametric amplifiers are so sensitive that the noise from the galaxy threatens to limit communication over much of the radio spectrum. Fig. 7-1 shows that cosmic noise increases rapidly at fre-

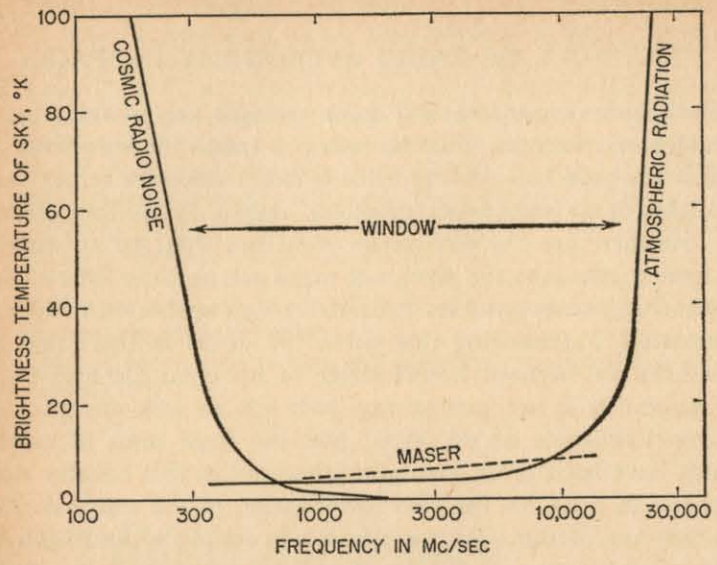


FIG. 7-1 Minimum levels of natural radio noise. It has been assumed that the antenna is directed toward the zenith at a time when a region of minimum cosmic radio noise is overhead. The dashed line shows the noise level of an advanced maser amplifier. (After F. D. Drake in *Telescopes*, edited by G. P. Kuiper and B. M. Middlehurst, University of Chicago Press, Chicago, 1960.)

quencies below 800 Mc/sec, while above 10,000 Mc/sec radio noise from water vapor and oxygen in the earth's atmosphere shoots up precipitously. The delineation of the "window" in the noise spectrum between the two curves is an important practical by-product of radio astronomy, for it is evident that frequencies within this window are most effective for direct communication between the earth and other objects in space. Radio engineers must also remember that the sun and Jupiter are extremely noisy bodies which are certain to interfere with any communication system that must "look" in their direction, unless the frequency is selected with great care. By the same token, however, solar or Jovian radio noise might well be used to actuate "homing" devices in spacecraft, making these bodies the easiest targets in the solar system.

In providing accurate measurements of the positions and intensities of large numbers of discrete sources, radio astronomers have covered the sky with a network of convenient reference points. Engineers are now using these radio stars to calibrate their own antennas for sensitivity, beamwidth, and pointing accuracy. They are also using astronomical observations of the bending or refraction of radio waves in the ionosphere to correct their measurements of the positions of man-made objects in space.

Nor have the contributions of radio astronomy to technology been confined entirely to space problems. As early as 1954 a solar "radio sextant" was developed for the U. S. Navy in order to make celestial navigation possible in cloudy weather.[2] Utilizing the one-centimeter microwave radiation from the sun, this instrument provides even greater accuracy than a conventional optical sextant. Recently it was announced that the Navy's Polaris submarines will obtain the precise "fixes" needed for missile launchings in overcast weather by means of a "radiometric sextant" that can detect radio noise from either the sun or the moon. It is not difficult to imagine the extension of this technique to include the more intense radio stars.

But what about radio astronomy's direct contribution to our surprisingly meager store of knowledge about even the nearer bodies of the solar system? The results already achieved are of considerable significance to both manned and unmanned space exploration projects. We remember at once the rather encouraging measurements of the moon's heat, which indicate that stable temperatures may be found just a few feet beneath the lunar surface. We also remember the rather forbidding discovery that an intense Jovian radiation belt confronts future space travelers, and the even more menacing revelation of a Venusian surface temperature in excess of 300° C. When we consider that it costs $18.5 million to send a single space probe on a "fly-by" mission past Venus—and probably even more to land an instrument package on the surface of the planet—the value of such advance information becomes impressive.

Commenting on the radio observations of Venus and Jupiter, Dr. F. D. Drake of the National Radio Astronomy Observatory said, "It might be noted that these results . . . have an extremely

large dollars and cents value. Had we not known of them, our first space probes to the near vicinity of these planets would undoubtedly have been improperly instrumented, perhaps to such an extent that the mission would have been a complete failure. Thus the radio astronomers have probably saved the expense of at least two space probes, which actually exceeds considerably all the money ever spent on radio astronomy." [3] Drake's point was well illustrated by the satellite Explorer I, which "discovered" the earth's Van Allen belts in 1958. Because its overly sensitive Geiger counter was completely jammed by the unexpectedly high radiation level that was encountered, the satellite could provide no data on the actual intensity of the belts. A like fate might well have awaited our first Jupiter probe, had we not known in advance of that planet's radiation belt. And it is easy to imagine the inglorious end of an unprotected instrument package landing in a Venusian environment considerably hotter than the oven temperatures used in roasting meat!

On August 27, 1962, an Atlas-Agena rocket launched a Mariner spacecraft on a 180-million-mile trajectory toward Venus. The flight was a brilliant success, which rightfully attracted public acclaim. Not only did the spacecraft telemeter back to earth an enormous amount of information about interplanetary space, but on December 14 it passed within 21,645 miles of its target planet before going into orbit about the sun.

The Mariner represents a wedding between the direct exploration of space and planetary radio astronomy, for the most important instrument on board the spacecraft is a 20-inch parabolic antenna (see Plate XV), which made three scans of the surface of Venus as Mariner sped by. Signals from the antenna were analyzed by a microwave radiometer operating at wavelengths of 1.35 and 1.90 cm. These wavelengths were selected because 1.35-cm radiation is absorbed by water vapor, so that a weaker signal in this band would indicate the presence of moisture in the Venusian atmosphere. The 1.90-cm signal, which is not strongly attenuated by water vapor, was intended to penetrate the atmosphere and settle the vexing question of the planet's surface temperature.

The 1.35-cm data have not been fully analyzed, and indeed

there seems to be a question as to whether this channel functioned properly. A preliminary analysis of the 1.90-cm data has yielded a surface temperature of 700°K, which is in good agreement with the ground-based radio measurements. Even more important, Mariner was able for the first time to *resolve* the disc of the planet at radio frequencies—that is, to measure the variation in radio flux across the disc. Unfortunately for those who had hoped that the excess radio energy might come from a Venusian ionosphere (see p. 55), the 1.90-cm signal actually decreased near the edge of the planet. This, of course, is the direct reverse of what would have occurred if the radio flux were coming largely from a layer surrounding Venus. While experience teaches us to be a bit skeptical about the finality of so-called "crucial experiments," there can be little doubt that the data which Mariner radioed back to earth dealt a severe blow to our hopes of finding life as we know it on our sister planet.

ARE WE ALONE?

Manned exploration of the solar system must rank as the most dramatic adventure since the great navigators circled the globe in the fifteenth and sixteenth centuries. Yet there is one element missing that would make this adventure even more exciting. We really do not expect to find intelligent life—as we know it—on any of the other planets that circle our sun. The reasons for this pessimism will be evident to those who have digested the data of Chapter 3. In terms of our present knowledge there simply does not appear to be another planet in the solar system capable of supporting higher life as we understand it.

Does this mean, then, that we are alone in the universe? During the past century scientific opinion on this question has completed a full circle, going from optimism to pessimism and back again to optimism.

For several hundred years after the telescope first revealed the planets as cold bodies similar to the earth, it was assumed as an act of simple faith that they must have been created in order to be habitable. In a textbook on practical astronomy published in 1760, the British teacher R. Wetherald expressed this conviction

in a characteristic manner which today seems charming, if a bit ingenuous: "If Jupiter has four moons, it is to give it light in the night-time. But to what purpose this light if that planet is not inhabited. The planets therefore must be inhabitable worlds." [4]

In a similar way, as soon as astronomers realized that the stars are actually other suns, it was assumed that they must be surrounded by habitable planets. At the end of the seventeenth century the famous Dutch physicist, mathematician, and astronomer, Christian Huygens, wrote, "Why may not every one of these stars or suns have as great a retinue as our sun, of planets, with their moons, to wait upon them? . . . They must have their plants and animals, nay and their rational creatures too, and those as great admirers, and as diligent observers of the heavens as ourselves. . . ." [5]

The decline of this spirit of optimism came about—largely in the present century—because the prevailing theories maintained that the solar system had been created only as the result of an extremely improbable accident. It was assumed that the sun had experienced a near-collision with another star, and that during this encounter a large tidal jet was torn out of the solar surface. Later, according to the theory, this jet condensed to form the planets. As our knowledge of the structure of the galaxy improved, it became evident that the average density of stars in space is so low that such collisions must be extremely rare. In fact, present statistics suggest that only one or two of the 100 billion stars that make up our galaxy might have undergone such an encounter. If planets are indeed formed in such an odd manner, ours might well be the only solar system in the galaxy!

During the past decade there has been a return to a point of view championed by Kant in the eighteenth century—namely, that stars and planets condense in a natural way out of the vast clouds of dust and gas that permeate the galaxy. Otto Struve has called attention to the fact that most of the hotter stars spin quite rapidly on their axes, whereas the cool stars that resemble our sun generally rotate much more slowly. This puzzling difference can be explained if, during the condensation process, planets form around the cooler stars, carrying off most of the angular momentum that otherwise would appear in the rotation of the

star itself. Thus it is possible that planet formation is a natural by-product of the development of certain common types of stars, in which case a significant fraction of the stars of our galaxy must be accompanied by their own families of planets.

Does this mean, then, that bodies capable of supporting life as we know it are common? In order to answer this question it is clearly not enough merely to know that a certain percentage of the stars are probably surrounded by planets. We must also know what fraction of these planets are at the proper distances from their central suns so that they are neither too hot nor too cold. And last, but far from least, we must know what proportion of these favorably situated bodies might be expected to provide suitable atmospheres and other environmental conditions. In his entertaining little book *Of Stars and Men* the noted astronomer Harlow Shapley concludes that perhaps one star in a million has a planet that meets all the necessary conditions.[6] Since there are 10^{11} stars in our galaxy, give or take a few, this implies that there must be 100,000 planets in the Milky Way capable of supporting higher organisms. If we wish to include the entire universe, consisting of perhaps 10^{22} stars, Shapley's estimate gives a total of 10^{16} habitable planets! Recently Su-Shu Huang of the Princeton Institute of Advanced Study re-examined this question in great detail, concluding that 1 or 2 percent of all stars may at one time or another support intelligent life.[7]

If a planet provides suitable conditions for life, does it necessarily follow that life will actually evolve on that body? Here we are clearly beyond the province of physics and astronomy, but the tendency of modern biology is to regard life as a natural phenomenon that will develop wherever a proper environment exists. Shapley has summed up the convictions of the majority of present-day astronomers: "Millions of planetary systems must exist, and billions is the better word. . . . On some of these planets is there actually life? Or is that biochemical operation strangely limited to our planet, limited to No. 3 in the family of the sun, which is an average star located in the outer part of a galaxy that contains a hundred thousand million other stars—and this local galaxy but one of millions of galaxies already on the records? Is life thus restricted? Of course not. We are not alone." [6]

AN EAR TO THE STARS

Shall we ever set foot on a planet belonging to another sun? Certainly not in the foreseeable future. Even if we could accelerate a vehicle to the speed of light, it would take eight years to make a round trip to the nearest star. To explore a reasonable sample of nearby stars would require a space voyage lasting many decades. How, then, shall we ever know if there are other intelligent beings in the universe? The only solution that seems to be within reach at the present time is radio communication (although the development of the *laser* suggests that signaling with light may eventually become a possibility). Quanta of electromagnetic energy are tireless messengers that will travel through space forever without needing food, water, or tranquilizers.

What are the technical requirements for interstellar—or even interplanetary—radio communication? Let us consider a transmitting antenna of area A_T separated by a distance D from a receiving antenna whose area is A_R. It is not difficult to show[8] that for a given wavelength λ the relationship between the received power P_R and the transmitted power P_T is

$$\frac{P_R}{P_T} = \frac{A_R A_T}{\lambda^2 D^2}. \tag{7-1}$$

To illustrate the use of this equation, let us estimate the smallest power that might be used to exchange signals with Mars when that planet is at its minimum distance of 34.5 million miles (1.82×10^{11} feet). If we are willing to agree that a signal can be detected if it at least equals the noise level in the receiver, we can let P_R equal the combined thermal noise of the receiver and the sky background. With an advanced maser amplifier operating at a wavelength of 21 cm, near the minimum of the noise curve in Fig. 7-1, an equivalent noise temperature of 10° K might be achieved. Then, if the bandwidth Δf of the system is set at the rather minimal value of 10 cps, Eq. 3-6 tells us that the noise level is

$$P_R = kT(\Delta f) = 1.38 \times 10^{-23} \times 10^{\circ} \times 10 \text{ cps} = 1.38 \times 10^{-21} \text{ watts.}$$

Since there are now a number of 85-foot parabolic antennas in

operation, let us assume that each of our antennas is of this size, so that $A_R = A_T = 5360$ square feet. By simple substitution in Eq. 7-1 we now get

$$P_T = \frac{P_R \lambda^2 D^2}{A_R A_T} = 0.75 \times 10^{-6} \text{ watt, or about one } \textit{microwatt.}$$

While this seems like a startlingly low power, it must be remembered that our calculation applies to bare *detection* of a steady signal under idealized conditions. If we wish actually to exchange useful information—that is, to vary or *modulate* the signal—the bandwidth of our system must be increased in proportion to the rate at which we plan to transmit data. This in turn will increase the receiver noise P_R and the required transmitter power P_T. For simple telemetry of instrument readings a bandwidth of several hundred cycles per second might be needed; for voice communication, several thousand cycles per second; and for "live" television broadcasts, not less than a megacycle per second. Further substantial increases in power would be necessary to make the system reliable under less than ideal conditions, but it nevertheless appears that communication within the solar system is feasible with quite modest powers. This conclusion makes it seem still more unlikely that higher civilizations exist on other planets of the sun's family. If there *were* within the solar system other societies that had advanced to the level of radio communication, we would almost certainly detect their transmissions and they ours.

But what of our original problem, that of communicating with nearby stars? Our most powerful transmitters, such as the Millstone radar, have peak powers P_T of about a million watts. If such a transmitter were being operated on another planet several light years away, could we detect it?

Let us rearrange Eq. 7-1 in the form

$$D = \frac{1}{\lambda} \sqrt{A_R A_T (P_T / P_R)}.$$

Assuming, as we did in the Mars problem, a wavelength of 21 cm, 85-foot antennas, and a noise level P_R of 1.38×10^{-21} watts, we find that D is 2.1×10^{17} feet, or 6.8 light years. According to a

rule of thumb devised by F. D. Drake, if we express the diameter of the receiving antenna in feet, then a transmitter of the Millstone type can be detected at a distance in light years equal to one-tenth of this diameter.[9] For our 85-foot antenna Drake's rule gives 8.5 light years, in good agreement with the result just obtained.

Since the nearest star is 4.3 light years away, we may conclude that interstellar signaling *is* feasible, on a marginal basis, with our present technology. There are about six stars within range of a transmitter-receiver combination such as we have been discussing. If the receiving antenna were the 250-foot radio telescope at Jodrell Bank, this number would increase to 100 stars, while the 1000-foot fixed paraboloid being constructed in Puerto Rico should reach out to a distance that encompasses 10,000 stars.

What are the chances that powerful radio signals are actually being beamed into space from other planetary systems, either in a deliberate attempt to communicate or for some other technical purpose? This is a question that no one can answer, but in 1960 scientists at the National Radio Astronomy Observatory felt that the odds were good enough to warrant devoting some of the time of their 85-foot radio telescope to a search for artificial signals from certain nearby stars. Known as "Project Ozma," the undertaking was led by Dr. Drake. As Observatory director Otto Struve remarked, "Unless we try we will never know."

A perplexing problem in such a search is the selection of a frequency at which to listen. Without some basis for an intelligent choice, the venture literally would be more futile than hunting for a needle in a haystack. In designing a special receiver for Project Ozma, Drake followed a suggestion made by Cornell physicists Giuseppe Cocconi and Philip Morrison, who argued that the only real landmark in the radio-astronomical spectrum is the 1420 Mc/sec frequency emitted by hydrogen (p. 7). The two men reasoned that it would be logical for scientists of an advanced society to choose this frequency for signaling across space, since they could expect other civilizations to have many of their most sensitive radio telescopes tuned to the hydrogen line, as is indeed the case here on earth. However, visualizing the outcry that would arise from terrestrial radio astronomers if our

society were to jam their instruments by powerful broadcasts on the hydrogen frequency, we might argue with equal force that 1420 Mc/sec is the one frequency at which *not* to expect signals!

In any event, Project Ozma has thus far given negative results. Of course, no one anticipated immediate success in a search as difficult as this, but each year technical advances will make the odds more favorable. Drake has said, "It appears probable that this project or a similar one will some day succeed in detecting an artificial signal. Needless to say, the scientific and philosophical implications of such a discovery will be extremely great." Radio astronomy holds forth promise of high adventure—that of establishing contact with other civilizations, many of which could be far more advanced than our own.

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ABOUT THIS BOOK: This straightforward account describes the new science of radio astronomy, how it has contributed to man's knowledge of the moon and the planets, and what this means in terms of the current space effort. Since this is the first book devoted to planetary radio astronomy, some attention is given to the history and techniques of the field. The text is largely non-mathematical; it reflects the authors' fascination with their work, and it will interest all scientifically literate people in this era of the great push into space.

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